

Issues in the Formation and Dissipation of the Electron Cloud

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My gratitude to:

A. Adelmann, G. Arduini, M. Blaskiewicz, O. Brüning, Y. H. Cai, R. Cimino,
I. Collins, O. Gröbner, K. Harkay, S. Heifets, N. Hilleret, J. M. Jiménez, R. Kirby,
G. Lambertson, R. Macek, K. Ohmi, M. Pivi, G. Rumolo, F. Zimmermann.



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Summary

- Motivation: better understand electron cloud (EC) dynamics
 - in particular: effect of secondary electron process
- Tools:
 - simulations (mostly code POSINST – Furman and Pivi); other codes by Ohmi, Zimmermann, Rumolo, Blaskiewicz, Adelmann,... also take SE into account
 - electron detectors (APS, SPS, PSR, RHIC – Harkay, Jiménez, Macek, Browman, Zhang,...)
- EC formation
 - primary processes: photoelectrons, residual gas ionization, beam-particle losses
 - secondary electron emission (SEY): may lead to beam-induced multipatcing (BIM)
 - examples:
 - sensitivity to secondary emission yield $\delta(E_0)$ (E_0 =incident electron energy)
 - secondary emission spectrum $d\delta/dE$ (E =emitted electron energy)
- EC dissipation
 - focus: mostly PSR, also APS and SPS: role of $\delta(\theta)$
- Scrubbing effect and conclusions



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Tools

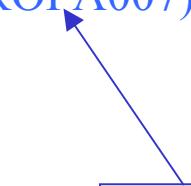
- Simulation

- detailed model for δ and $d\delta/dE$
- input data: measurements by R. Kirby, N. Hilleret, R. Cimino, I. Collins and others
 - St. St., Cu, Al, TiN
- electron cloud is dynamical
- beam is a prescribed function of time, space

- Electron detectors

- RFA (Harkay and Rosenberg, NIMPR **A453**, 507 (2000); PRSTAB **6**, 034402)
 - installed at APS, PSR, BEPC, ANL IPNS RCS (ROAB003; ROPA007)
 - measure I_{ew} and $d\delta/dE$ at chamber wall (“prompt” electrons)
- “sweeping detector” at PSR (Browman, Macek)
 - installed at PSR
 - measure EC density in the bulk (“swept” electrons) (ROAB003)
- strip detector at SPS, COLDEX, PUs
 - (Jiménez et al., PAC03) (TOPC003; TPPB054)
 - strip detector in an adjustable B field

PAC03 refs. in blue



EC formation: basics

- Electron charge conservation in a given chamber section
 - assuming no antechamber, no net end-losses
 - assumes 3 primary processes:

- photoelectrons
- residual gas ionization
- beam-particle losses

$$\dot{N}_{pr} = \dot{N}_{ph} + \dot{N}_{ion} + \dot{N}_{pl}$$

$$\begin{aligned}\dot{N}_e &= \underbrace{(\dot{N}_{ph} + \dot{N}_{ion} + \dot{N}_{pl})}_{\text{primaries}} + \underbrace{(\dot{N}_{sec} - \dot{N}_{col})}_{\text{net secondaries}} \\ &= \dot{N}_{ph} + \dot{N}_{ion} + \dot{N}_{pl} + (\delta_{\text{eff}} - 1)\dot{N}_{col}\end{aligned}$$

Assume: $\dot{N}_{pr} \propto \lambda_b(t)$ = beam line density

$$\dot{\lambda}_e(t) = v_b n'_{pr} \lambda_b(t)/Z + (\delta_{\text{eff}} - 1)pI_{ew}$$

(M. Blaskiewicz)

Z=beam particle charge

p=chamber x-section perimeter

I_{ew} =e⁻ flux at wall [A/m²]

n'_{pr} =primary production rate [m⁻¹]
per beam particle



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EC formation: primary e^- rate of creation

- Electron production rate per beam particle per unit length of beam trajectory:

$$n'_{pr} = \dot{n}_{pr}/v_b \quad n'_{pr} = \dot{n}_{pr}/v_b = n'_{e(\gamma)} + n'_{e(ion)} + n'_{e(bpl)}$$

$$n'_{e(\gamma)} = Y_{\text{eff}} n'_{\gamma}$$

$$n'_{e(bpl)} = \eta_{\text{eff}} n'_{bpl}$$

$$n'_{e(ion)} [\text{m}^{-1}] = 3.3\sigma_i [\text{Mbarn}] \times p_{vac} [\text{Torr}] \times \frac{294}{T [\text{K}]}$$

v_b = beam speed

Y_{eff} = eff. quantum efficiency (e^- yield per γ)

σ_i = ioniz. cross-section per beam particle

p_{vac} = vac. pressure

T = temperature

η_{eff} = eff. e^- yield per (beam particle)-wall collision

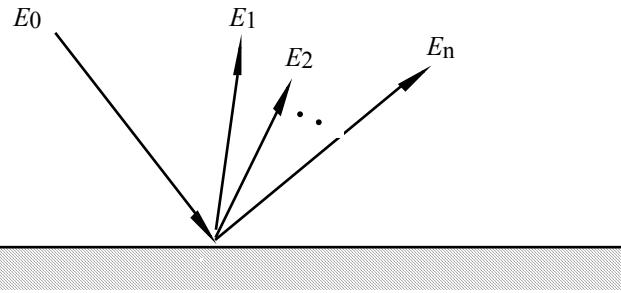
n'_{bpl} = beam particle loss rate per unit length per beam particle



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Secondary e^- emission

Three main components of emitted electrons:



elastics: $\delta_e = \frac{I_e}{I_0},$

rediffused: $\delta_r = \frac{I_r}{I_0},$

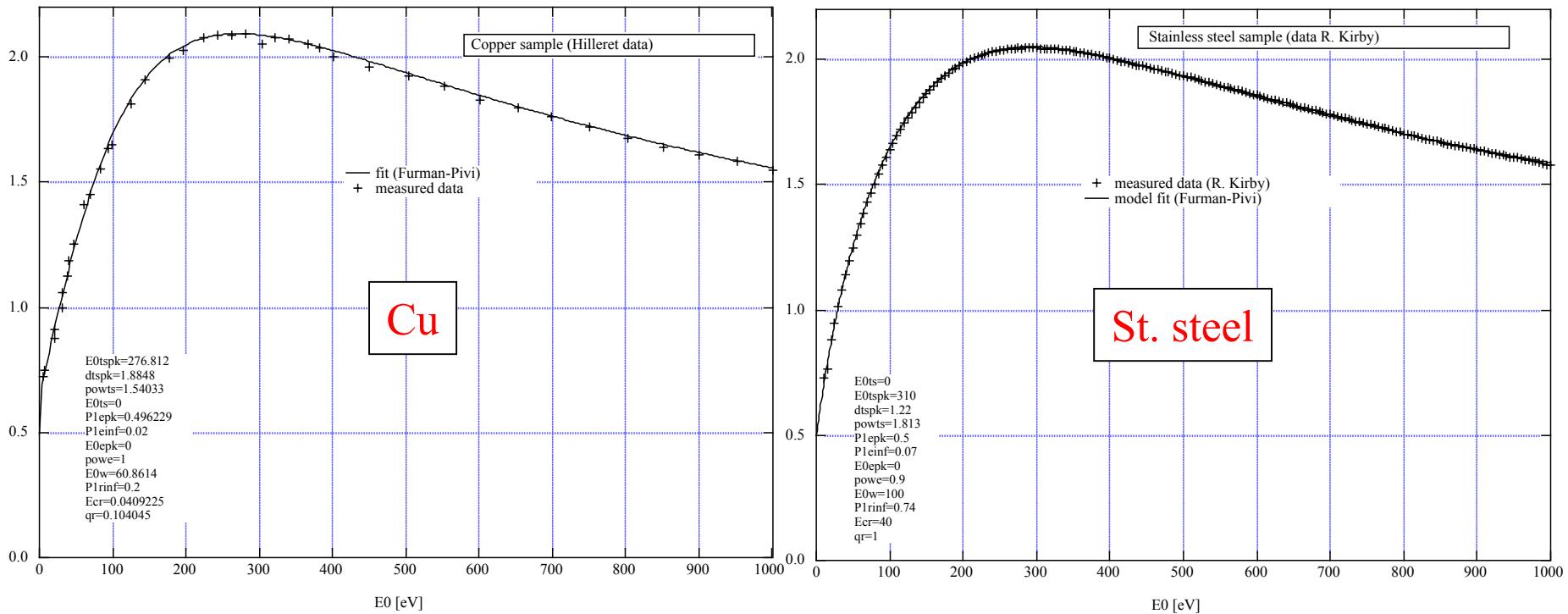
true secondaries: $\delta_{ts} = \frac{I_{ts}}{I_0}$

NB: $d\delta/dE$ is different for e, r and ts!!!

Simulation (Furman-Pivi, PRSTAB 5, 124404):

- event=one electron-wall collision
- instantaneous generation of n secondaries (or absorption)
- include E_0 and θ_0 dependence
- detailed phenomenological model for δ and $d\delta/dE$

Two sample measurements of the SEY

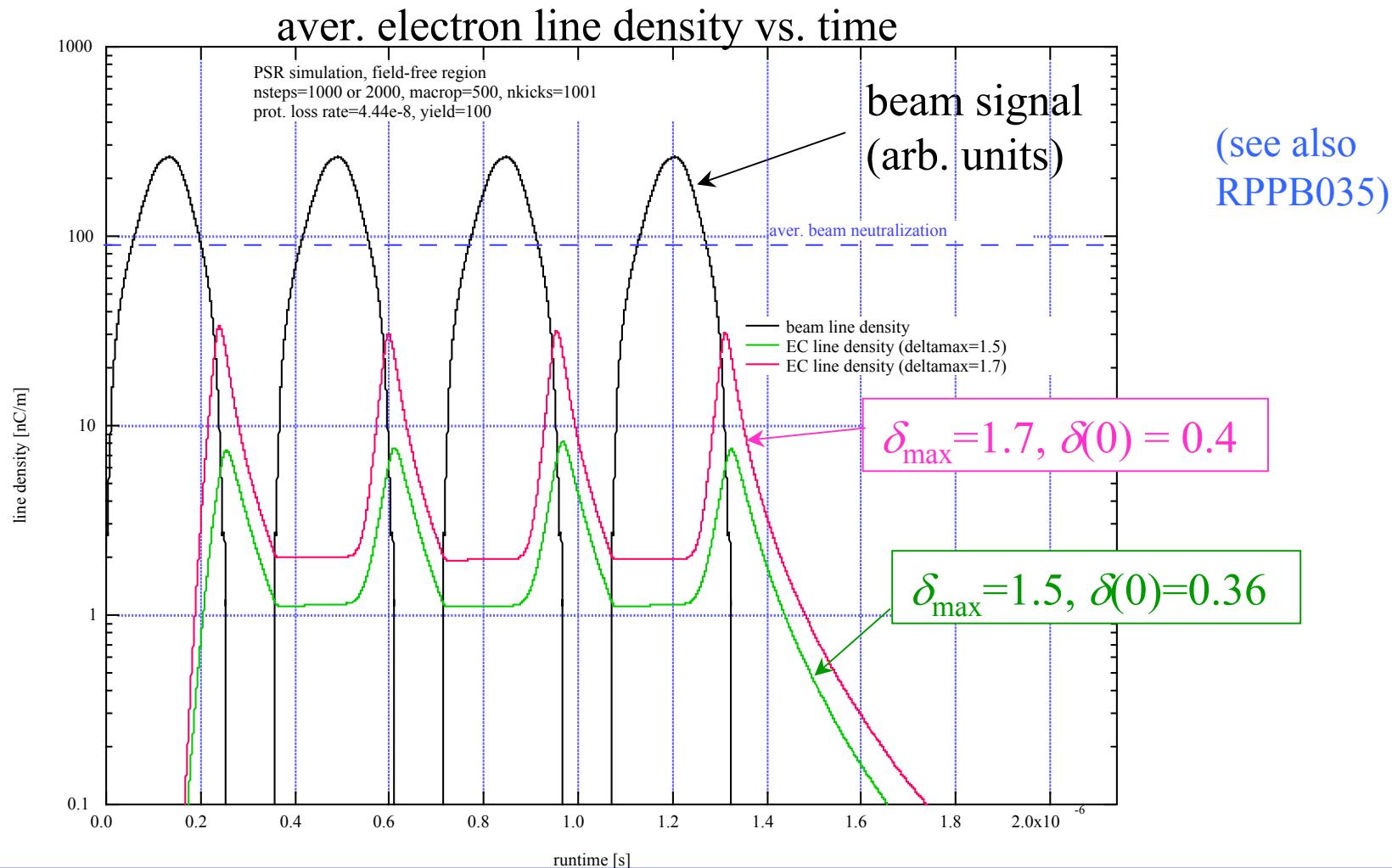


- caveat: samples not fully conditioned!

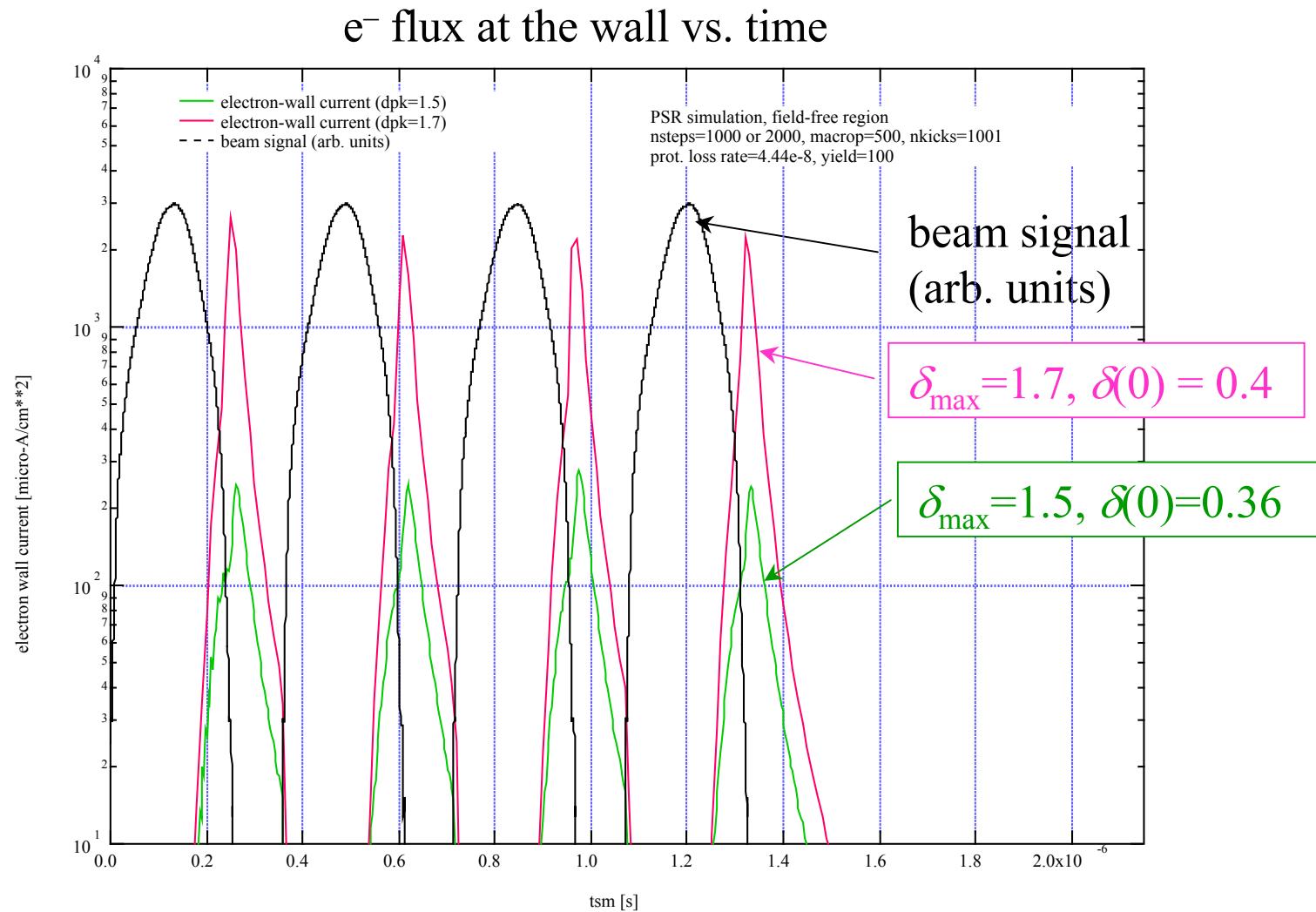
(N. Hilleret; R. Kirby)

PSR simulation: sensitivity to δ_{\max}

- stainless steel chamber, field-free region, $N = 5 \times 10^{13}$
- dominant primary process: proton losses: $n'_{e(bpl)} = \eta_{\text{eff}} n'_{bpl} = 4.44 \times 10^{-6} \text{ e/m}$

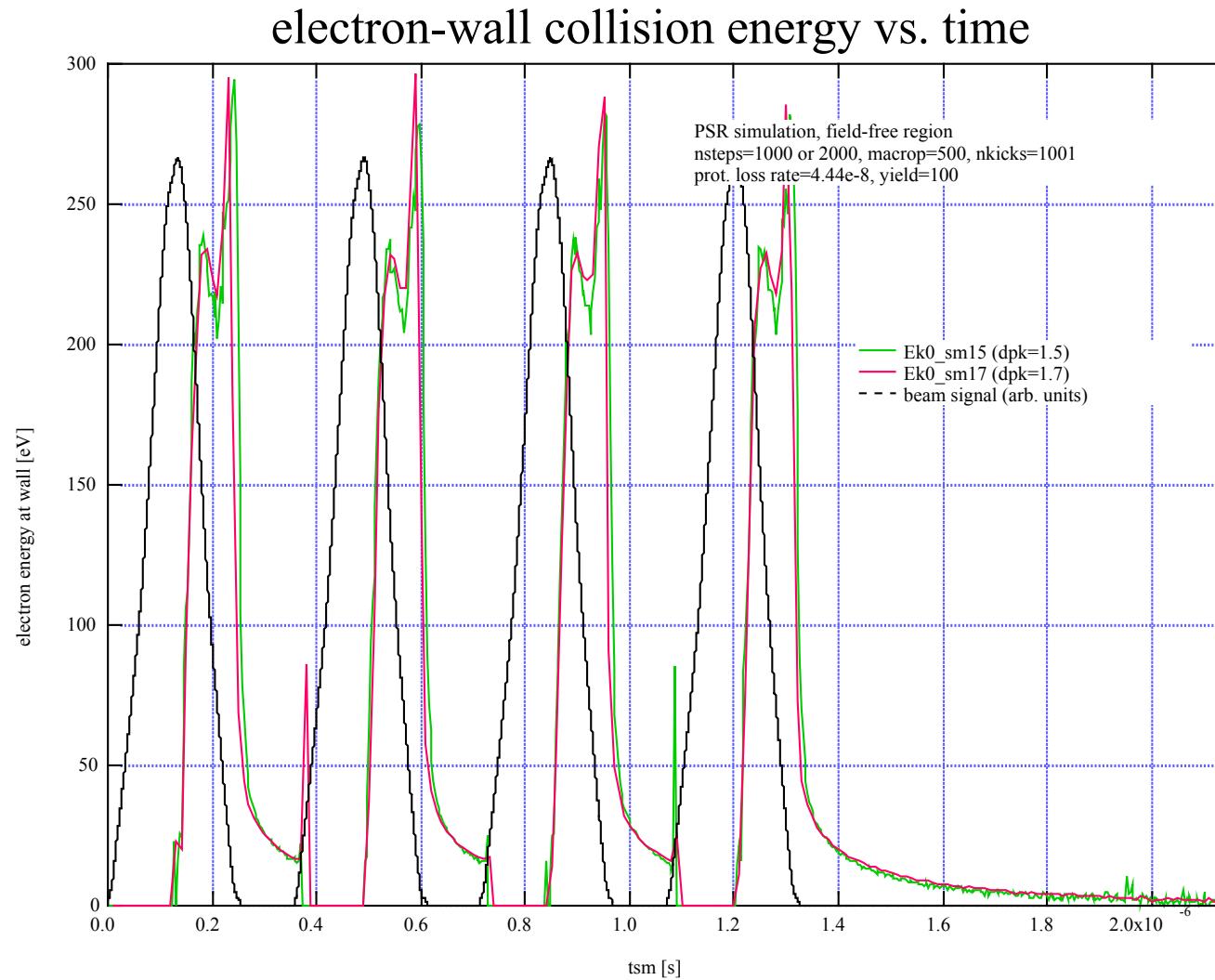


PSR simulation: sensitivity to δ_{\max}



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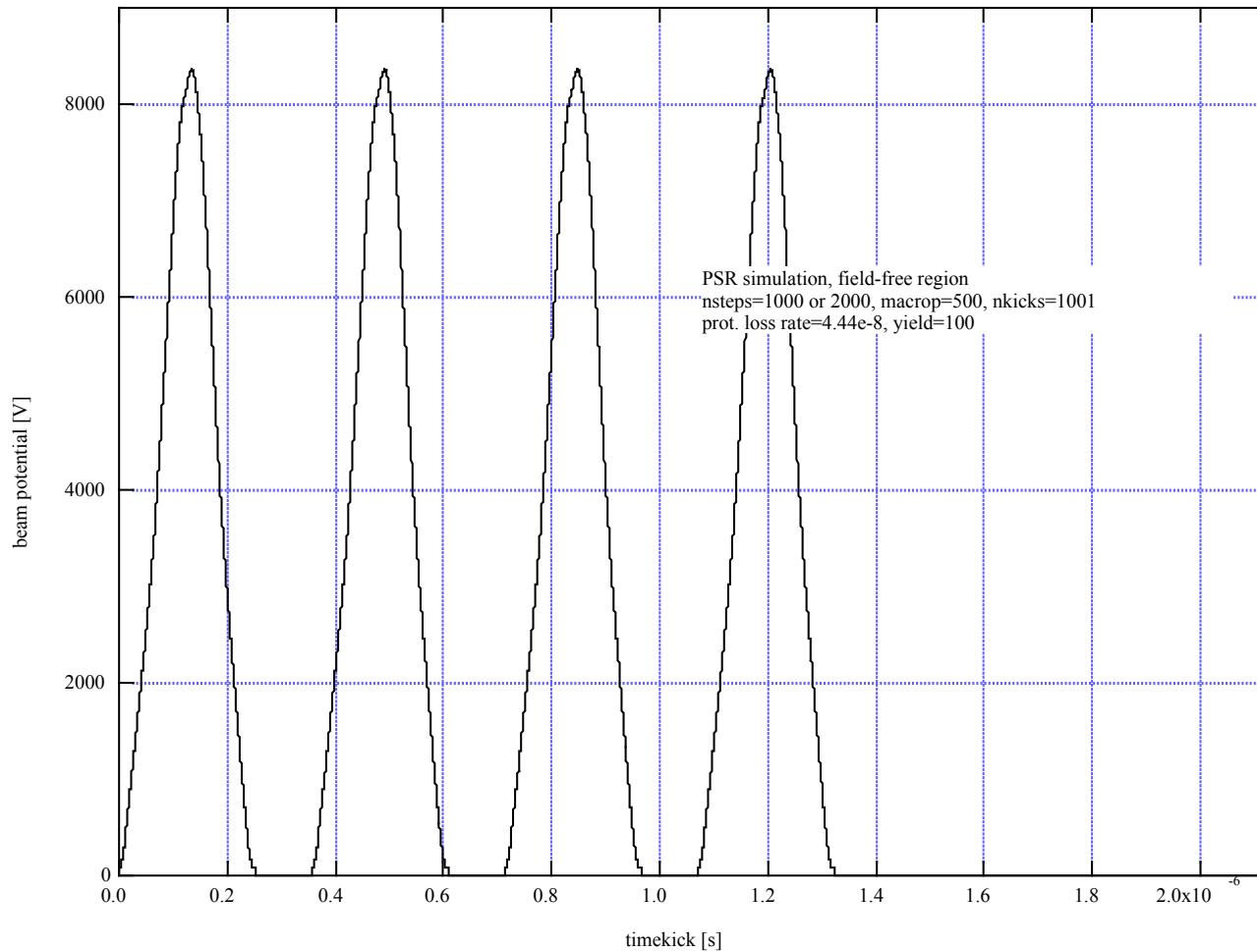
PSR simulation: sensitivity to δ_{\max}



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PSR simulation-contd.

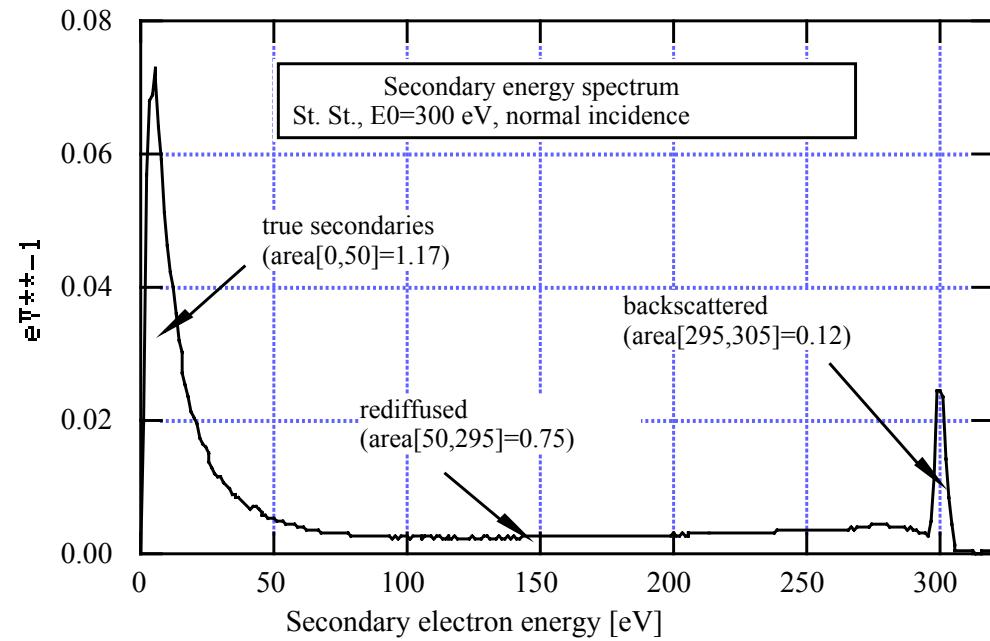
beam potential well vs. time



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Sample spectrum: $d\delta/dE$

- Depends on material and state of conditioning
 - St. St. sample, $E_0=300$ eV, normal incidence, (Kirby-King, NIMPR A469, 1 (2001))



st. steel sample

$$\delta = 2.04$$

$$\delta_e = 6\%$$

$$\delta_r = 37\%$$

$$\delta_{ts} = 57\%$$

Cu sample

$$\delta = 2.05$$

$$\delta_e = 1\%$$

$$\delta_r = 9\%$$

$$\delta_{ts} = 90\%$$

$$\delta_e + \delta_r = 43\%$$

$$\delta_e + \delta_r = 10\%$$

- Hilleret's group CERN: Baglin et al, CERN-LHC-PR 472.
- Other measurements: Cimino and Collins, 2003)



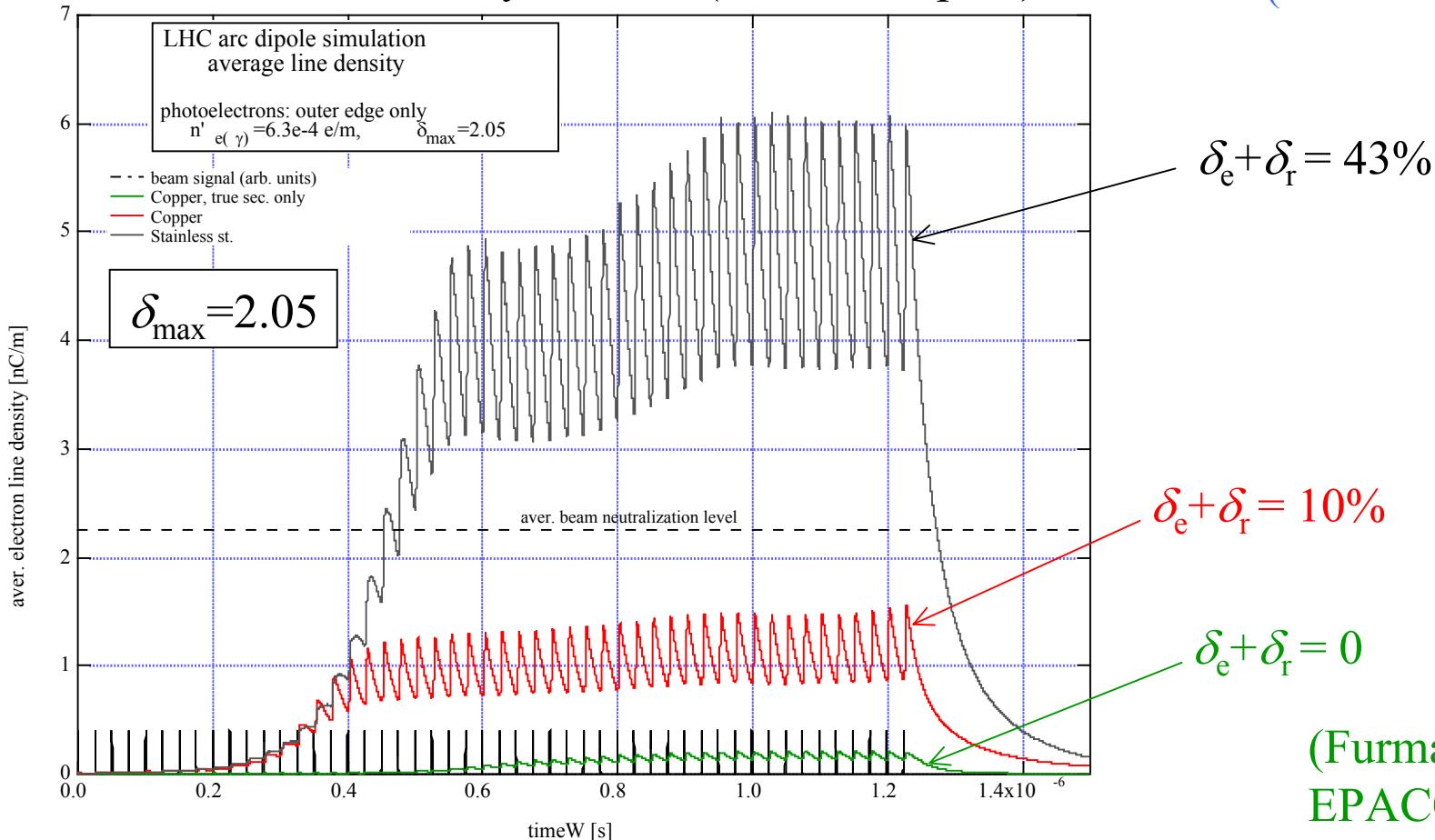
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Sensitivity to relative ratios of δ_e , δ_r and δ_{ts} : LHC

- LHC simulation δ_{\max} fixed at 2.05; $N = 1.05 \times 10^{11}$
- dominated by photoelectrons; $n'_{e(\gamma)} = Y^* n'_\gamma = 6.3 \times 10^{-4} \text{ e/m}$

electron line density vs. time (LHC arc dipole)

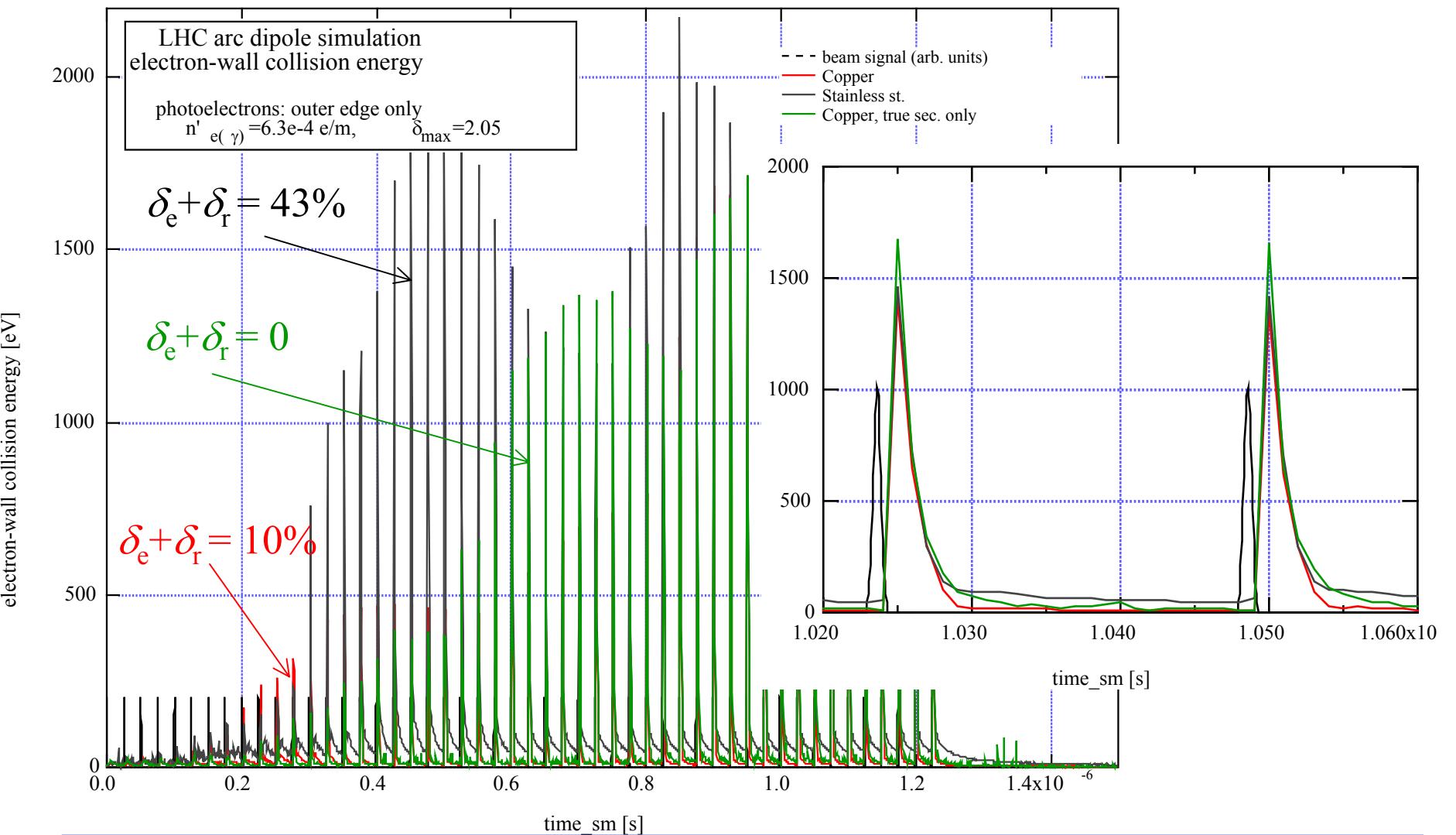
(see also: TPPB054)



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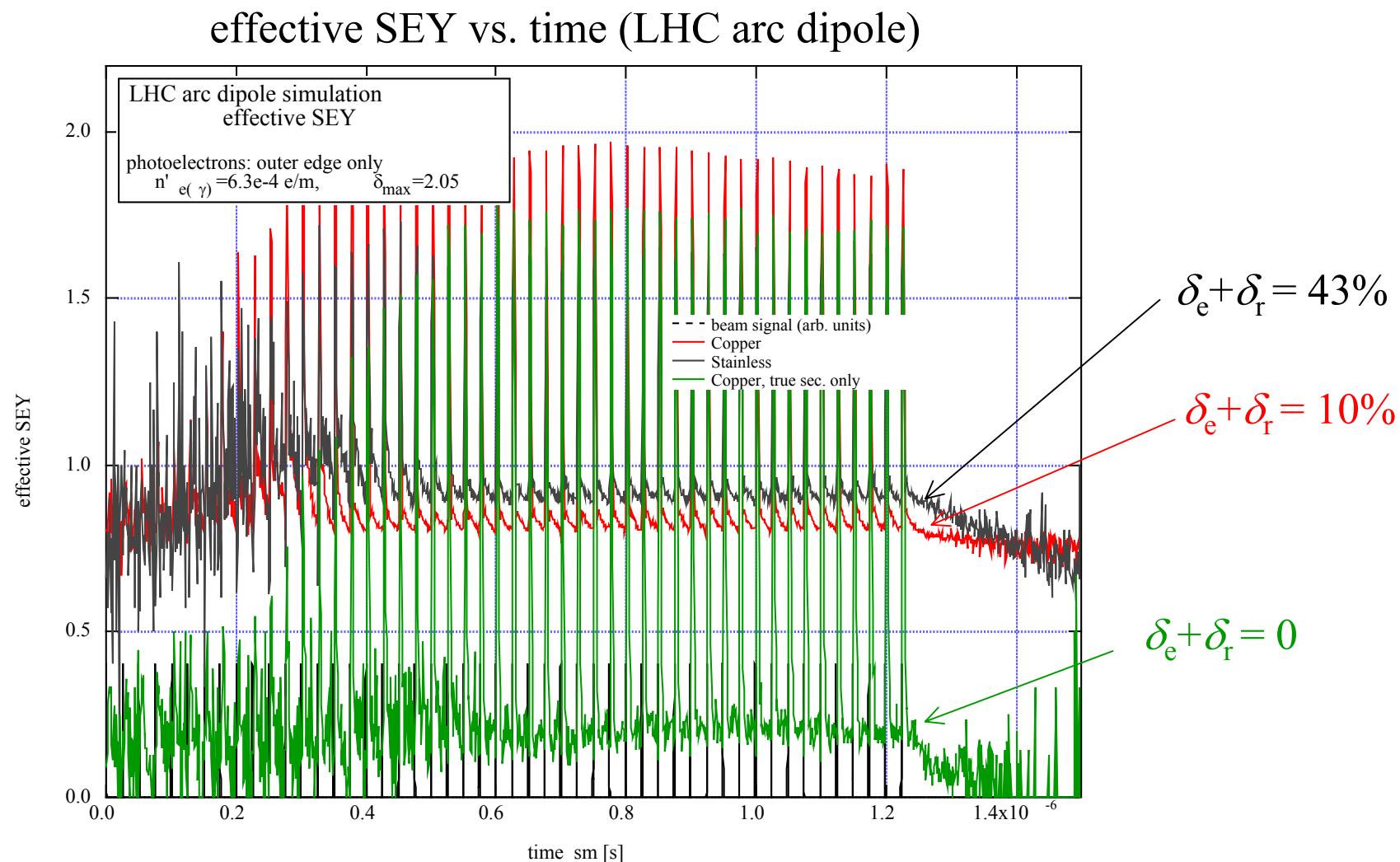
Sensitivity to relative ratios of δ_e , δ_r and δ_{ts} : LHC

e^- -wall collision energy vs. time (LHC arc dipole)



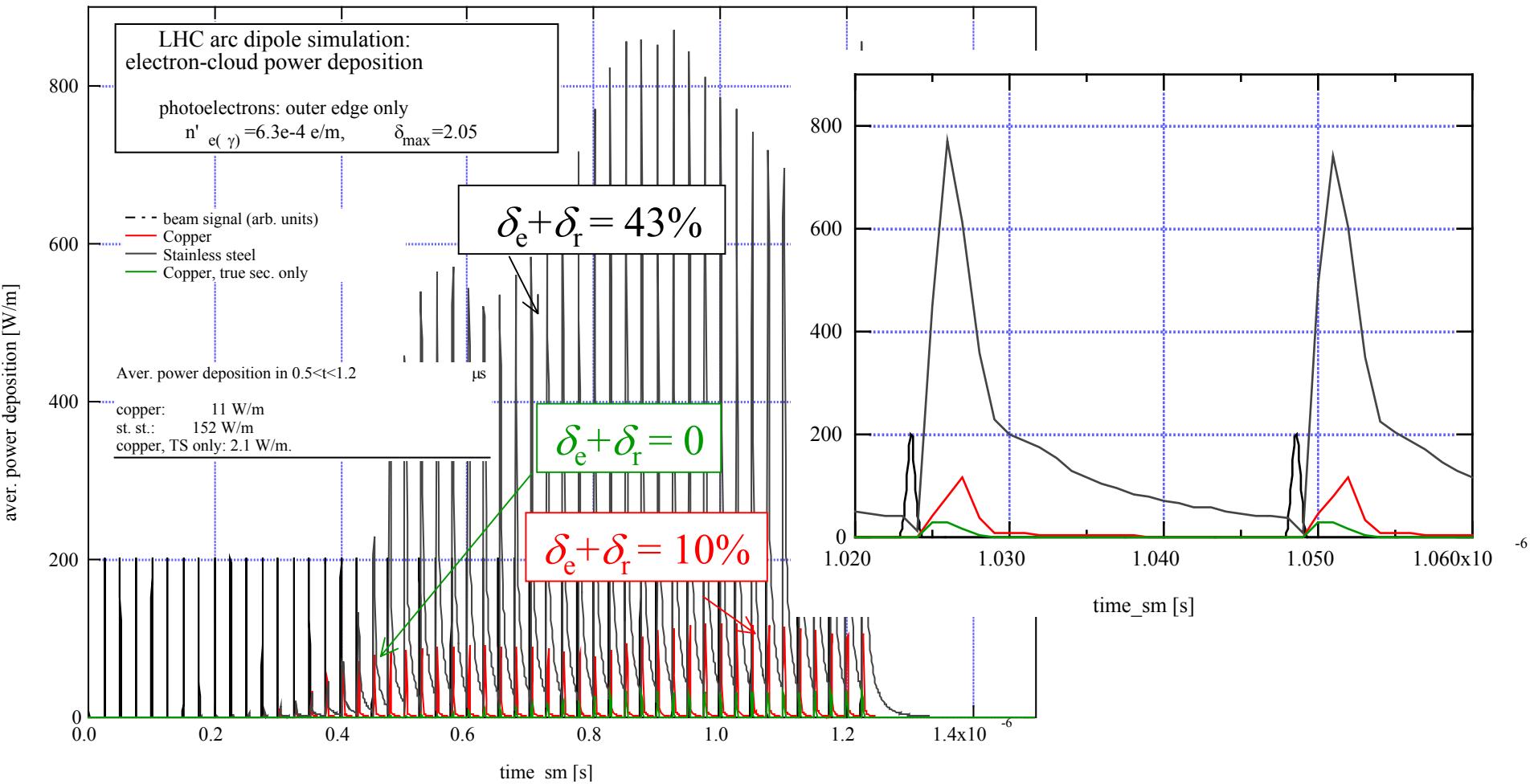
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Sensitivity to relative ratios of δ_e , δ_r and δ_{ts} : LHC



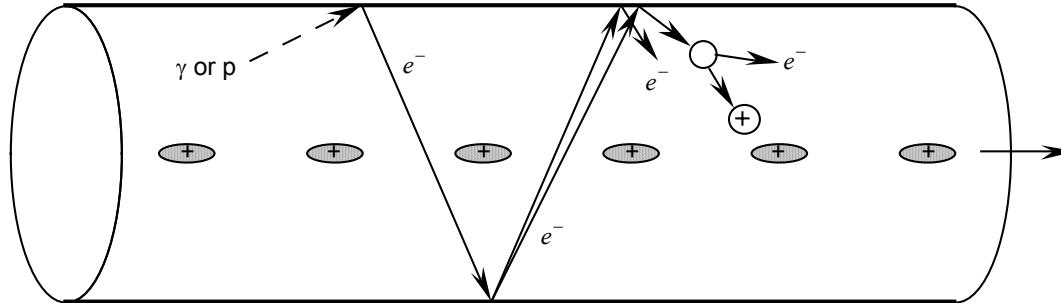
Sensitivity to relative ratios of δ_e , δ_r and δ_{ts} : LHC

power deposition vs. time (LHC arc dipole)



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EC formation: beam-induced multipacting (BIM)



- train of short bunches, each of charge $Q=NZe$, separated by s_b
- $\Delta t = e^-$ chamber traversal time
- b = chamber radius (or half-height if rectangular)

The parameter $G = \frac{ZNr_e s_b}{b^2}$ defines 3 regimes:
$$r_e = \frac{e^2}{mc^2} = 2.82 \times 10^{-15} \text{ m}$$

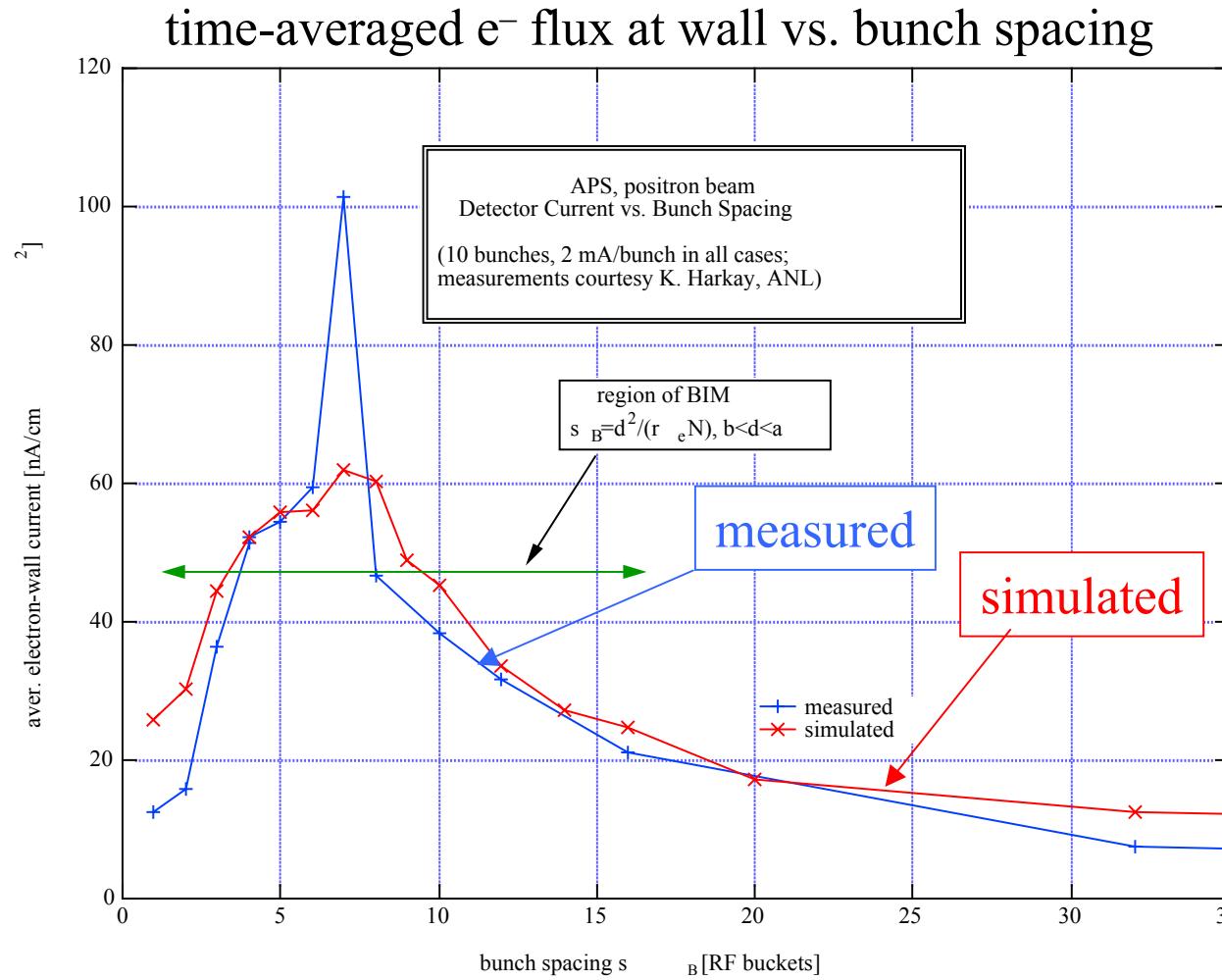
$$G \begin{cases} < 1 & \text{short bunch spacing } (s_b/c < \Delta t) \\ = 1 & \text{resonant (BIM) } (s_b/c = \Delta t) \\ > 1 & \text{long bunch spacing } (s_b/c > \Delta t) \end{cases}$$

(also for solenoidal field
if $T/2=s_b/c$: WOAA004)

If $G = 1$ and $\delta_{\text{eff}} > 1$, EC can grow dramatically (O. Gröbner, ISR; 1977)

BIM in the APS

- e^+ beam, 10-bunch train, field-free region



(see also:
RPPG02)

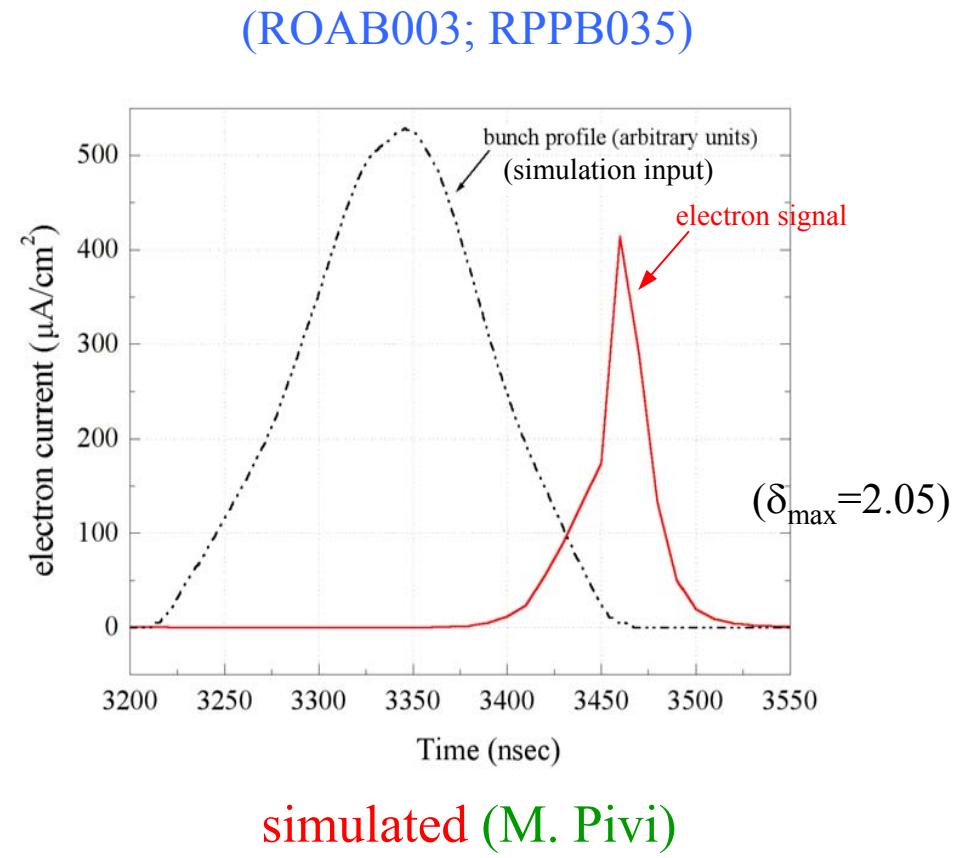
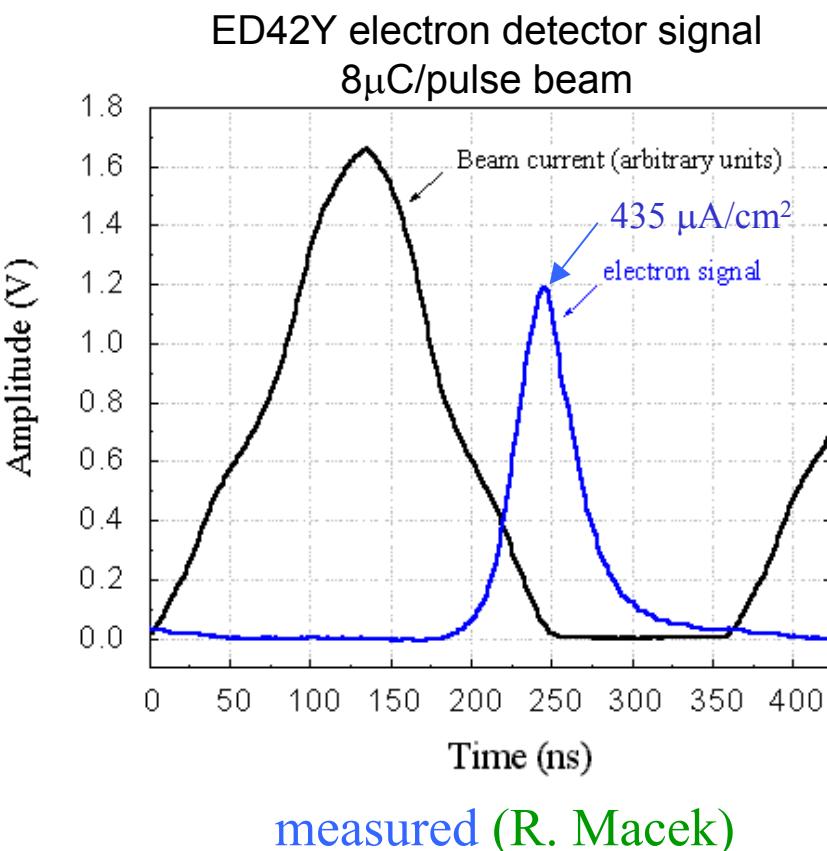
(Furman, Pivi, Harkay,
Rosenberg, PAC01)



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BIM for long bunches: case of PSR

- bunch length $\gg \Delta t$
 - a portion the EC phase space is in resonance with the “bounce frequency”
 - “trailing edge multipacting” (Macek; Blaskiewicz, Danilov, Alexandrov,...)



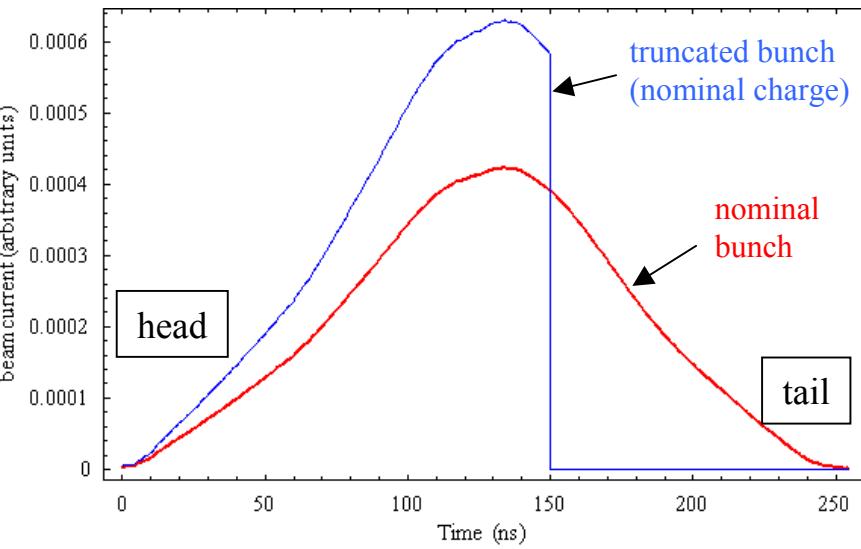
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BIM for long bunches: case of PSR-contd.

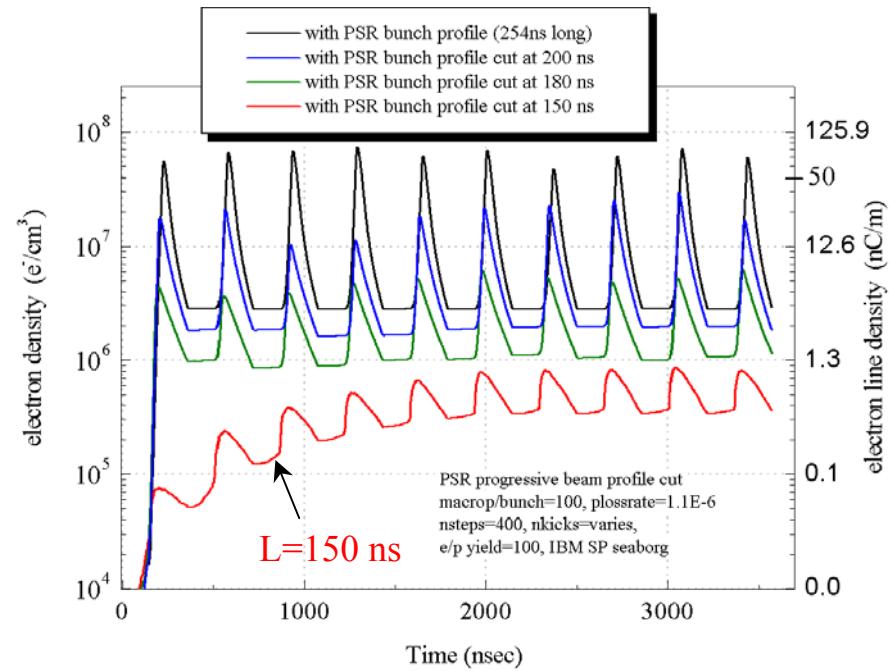
- simulated “experiment” in trailing edge multipacting:
— truncate bunch tail at fixed bunch charge

(RPPG024)

bunch profile



aver. e⁻ line density



- suppresses the resonance
- hard to put into practice!

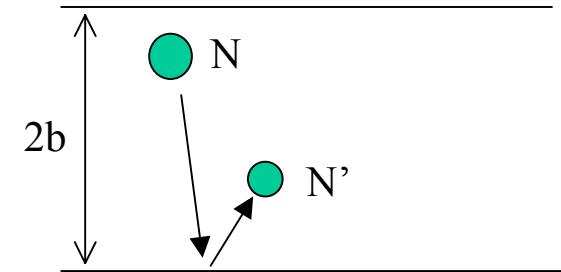
(M. Pivi)



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EC dissipation - simplest analysis

- beam has been extracted, or gap between bunches
- field-free region, or constant B field
- assume monoenergetic blob of electrons
- neglect space-charge forces



definition of δ_{eff} : $N' = \delta_{\text{eff}}N$

after n bounces: $N_n = Ne^{-n\Delta t/\tau}$

therefore: $\delta_{\text{eff}} = N'/N = e^{-\Delta t/\tau}$

where Δt = traversal time = $\frac{b}{c} \sqrt{\frac{2mc^2}{E}}$ and τ = dissipation time

$$\text{therefore } \delta_{\text{eff}} = \exp \left\{ -\frac{b}{c\tau} \sqrt{\frac{2mc^2}{E}} \right\}$$

simulations show that this formula works to within $\sim 20\%$

If not monoenergetic and not along a straight line, then

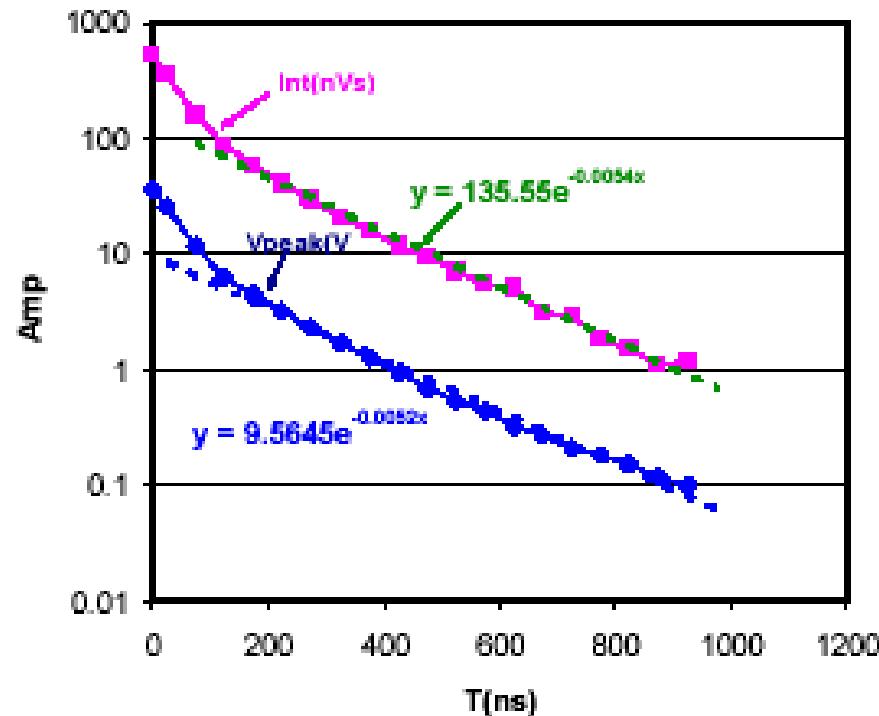
$$\delta_{\text{eff}} = K \int dE \rho_E(E) \delta_0(E) = \exp \left\{ -\frac{b}{c\tau} \int dE \rho_E(E) \sqrt{\frac{2mc^2}{E}} \right\} \quad \text{where } K=f(\text{angles}) \approx 1.1-1.2$$



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EC dissipation in PSR after beam extraction

- “Sweeping e⁻ detector”
 - measures electrons in the bulk
 - $\tau \approx 200$ ns
 - $\Rightarrow \delta_{\text{eff}} \approx 0.5$ if $E = 2\text{--}4$ eV
 - since $\delta_{\text{eff}} \approx \delta(0)$, you infer $\delta(0)$
 - well supported by simulations (see next slide)



(Macek and Browman)

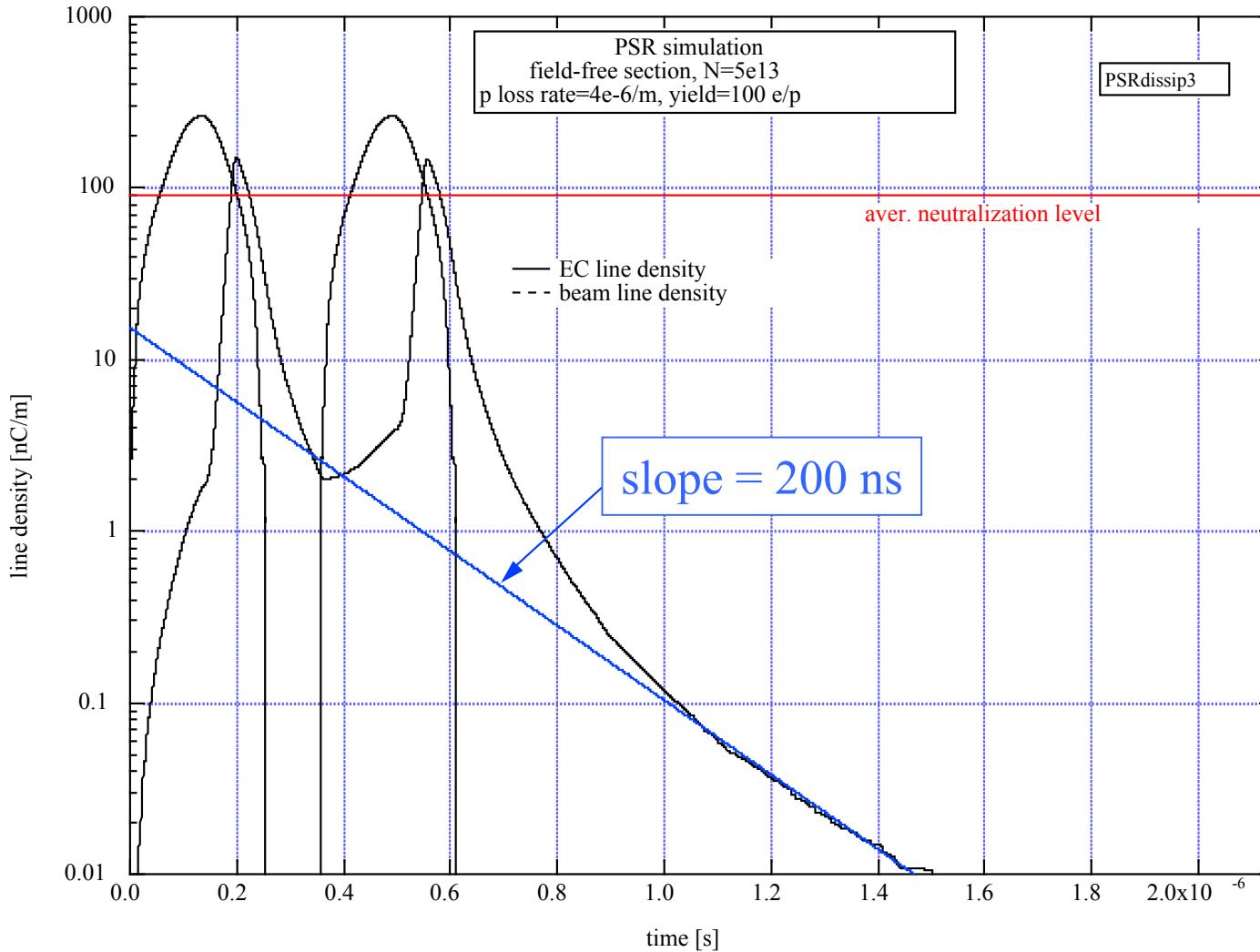
(RPPB035)



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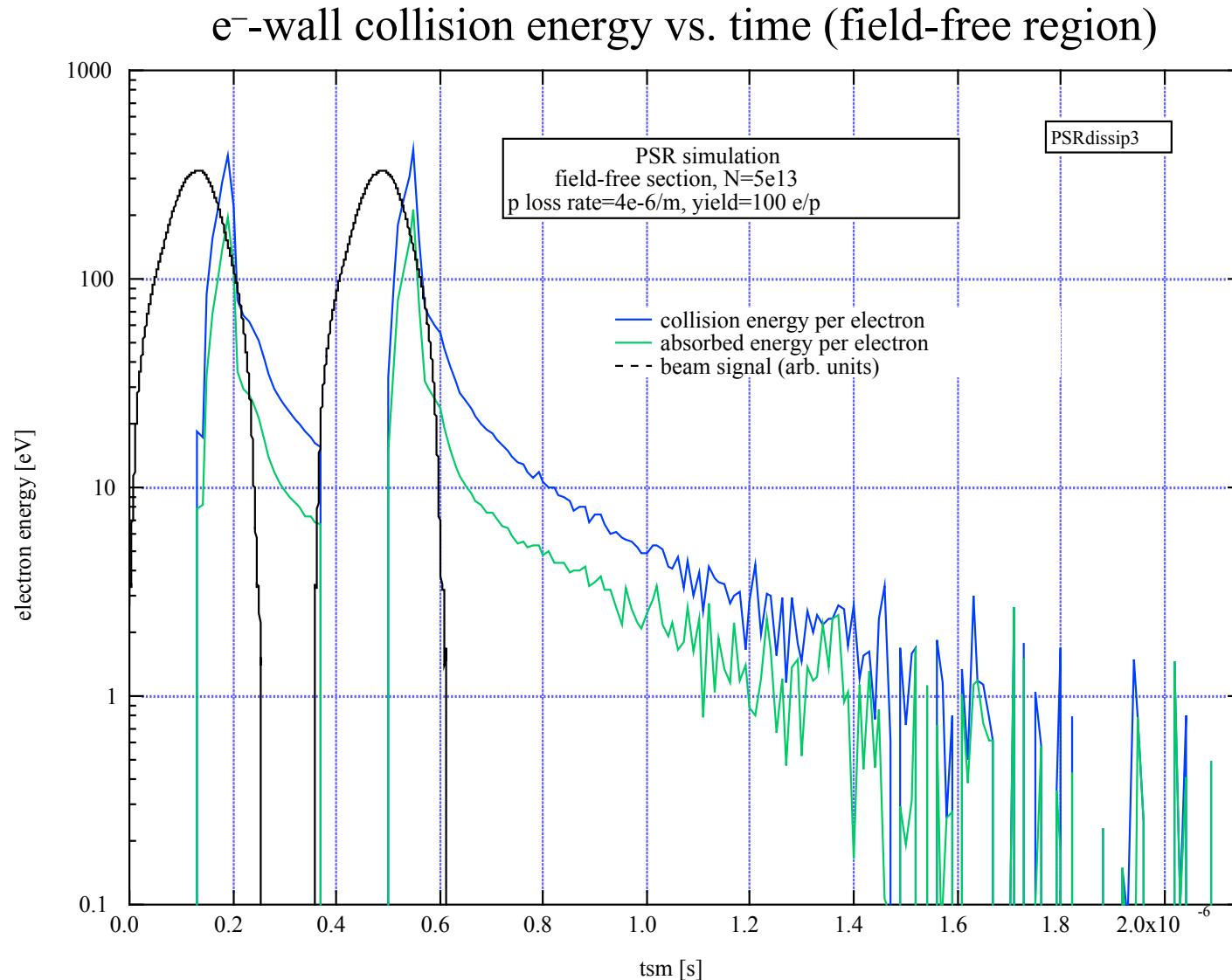
EC dissipation after beam extraction: PSR simulation

EC line density vs. time (field-free region)



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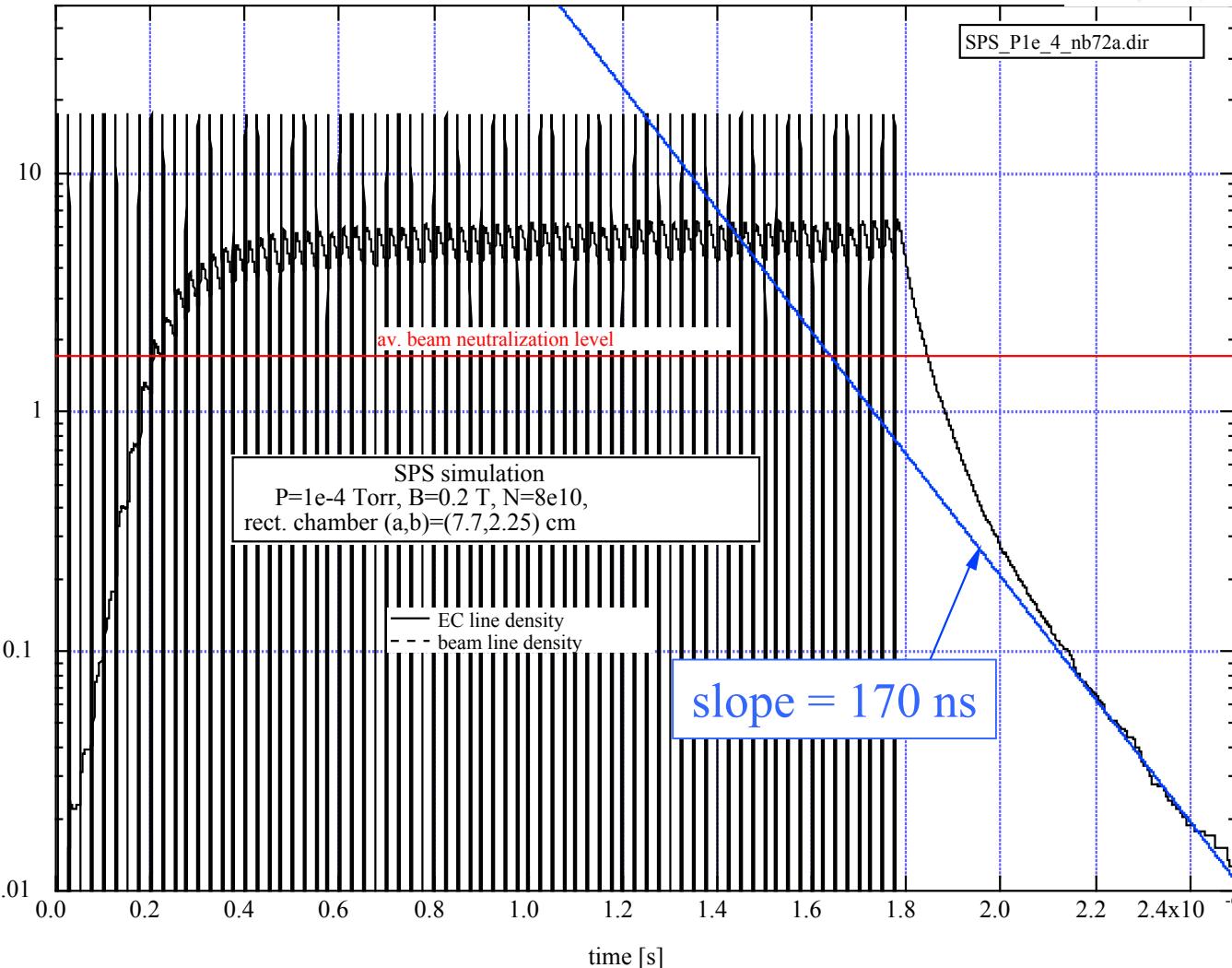
EC dissipation after beam extraction: PSR simulation



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EC dissipation after beam extraction: SPS simulation

- stainless steel chamber, dipole magnet, $B = 0.2$ T, $N = 8 \times 10^{10}$
- dominant primary process: residual gas ionization; $n'_{e(ion)} = 6.6 \times 10^{-4}$ e/m



NB: p_{vac} is
=> nominal

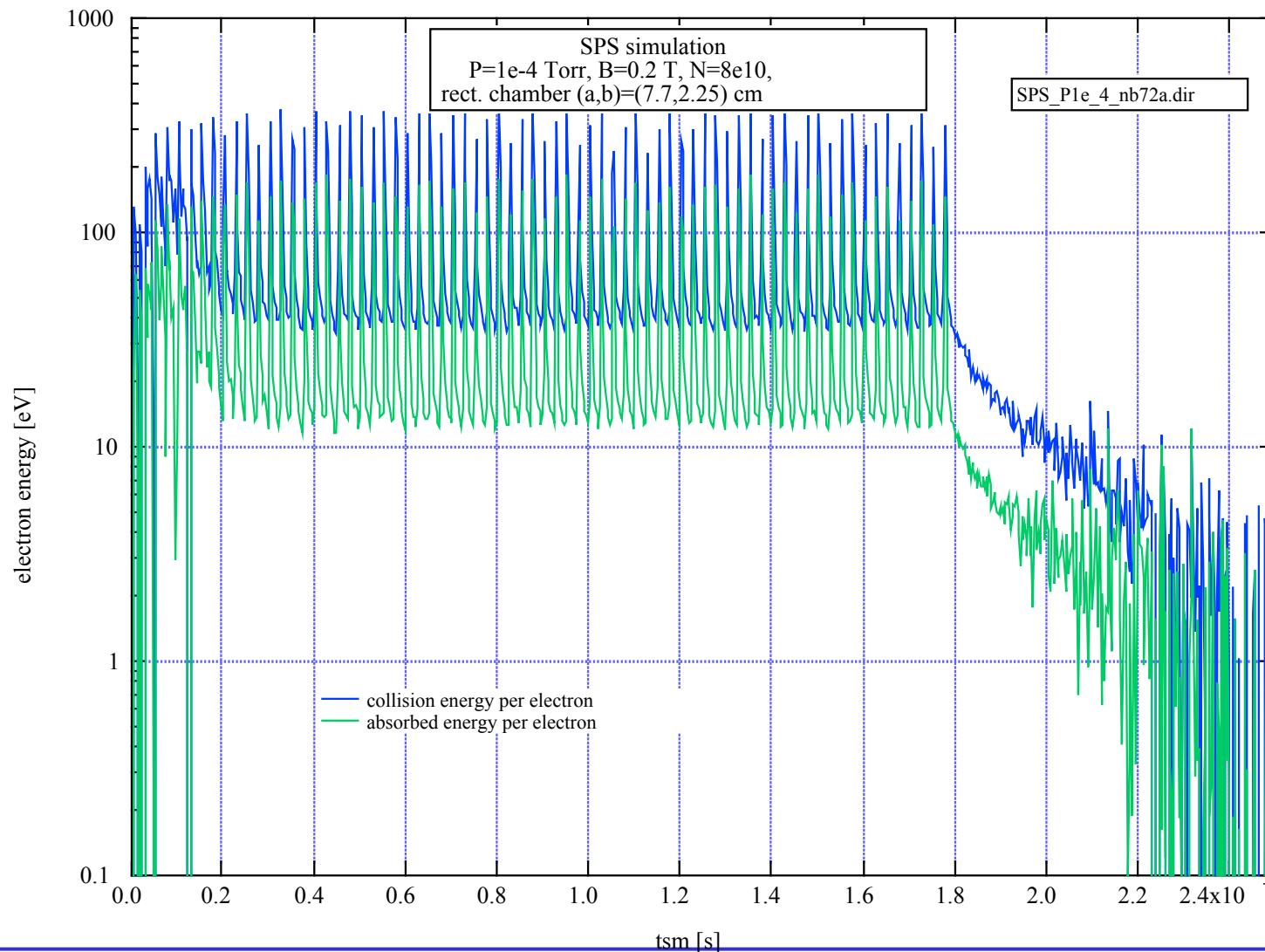
input SEY:
 $\delta_{max} = 1.9$
 $\delta(0) = 0.5$



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EC dissipation after beam extraction: SPS simulation

e⁻-wall collision energy vs. time (B-field region)



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Conditioning effects: beam scrubbing

- Decrease of SEY by e^- bombardment
 - self-conditioning effect for a storage ring: “beam scrubbing”
- SPS ECE studies (M. Jiménez; F. Zimmermann): (TOPC003)
 - 3+ years of dedicated EC studies with dedicated instrumentation
 - scrubbing very efficient; favorable effects seen in:
 - vacuum pressure
 - in-situ SEY measurements
 - electron flux at wall
 - e^- energy distribution in good agreement with simulations above 30 eV
 - TiZrV coating fully suppresses multipacting after activation

(see also: MOPA001; TPPB054)



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Conditioning effects: beam scrubbing

- PSR “prompt” e^- signal (BIM) is subject to conditioning: (R. Macek)
 - signal is stronger for st.st. than for TiN
 - sensitive to location and N
 - signal does not saturate as N increases up to $\sim 8 \times 10^{13}$
 - conditioning: down by factor ~ 5 in sector 4 after few weeks (low current)
- PSR “swept” e^- signal is not:
 - signal saturates beyond $N \sim 5 \times 10^{13}$
 - $\tau \approx 200$ ns, independent of:
 - N
 - location
 - conditioning state
 - st. st. or TiN
- Tentative conclusion: beam scrubbing conditions δ_{\max} but leaves $\delta(0)$ unchanged

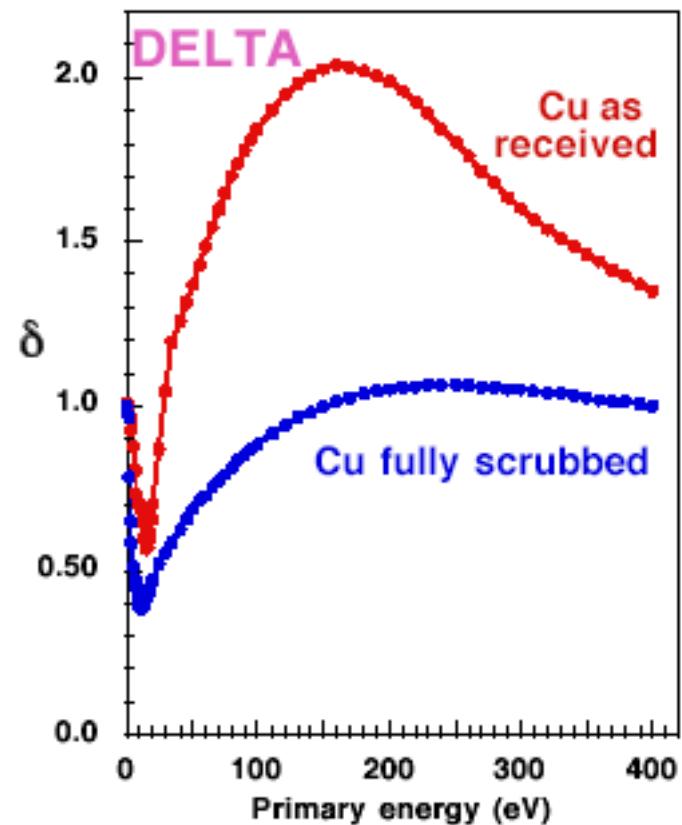


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Conditioning effects—contd.

- consistent with bench results for Cu found at CERN!
 - the result $\delta(0) \approx 1$ seems unconventional
 - if validated, it could have a significant unfavorable effect on the EC power deposition in the LHC
 - because electrons survive longer in between bunches

Copper SEY (CERN)



(R. Cimino and I. Collins, proc.
ASTEC2003, Daresbury Jan. 03)



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Conclusions

- A consistent picture of the ECE is emerging for
 - low-energy machines (long bunch, intense beam)
 - high-energy machines (short, well separated bunches)
 - methodical measurements and simulation benchmarks at APS, PSR and SPS are paying off
 - some interesting surprises along the way
- Quantitative predictions are becoming more reliable
 - we are growing older but wiser

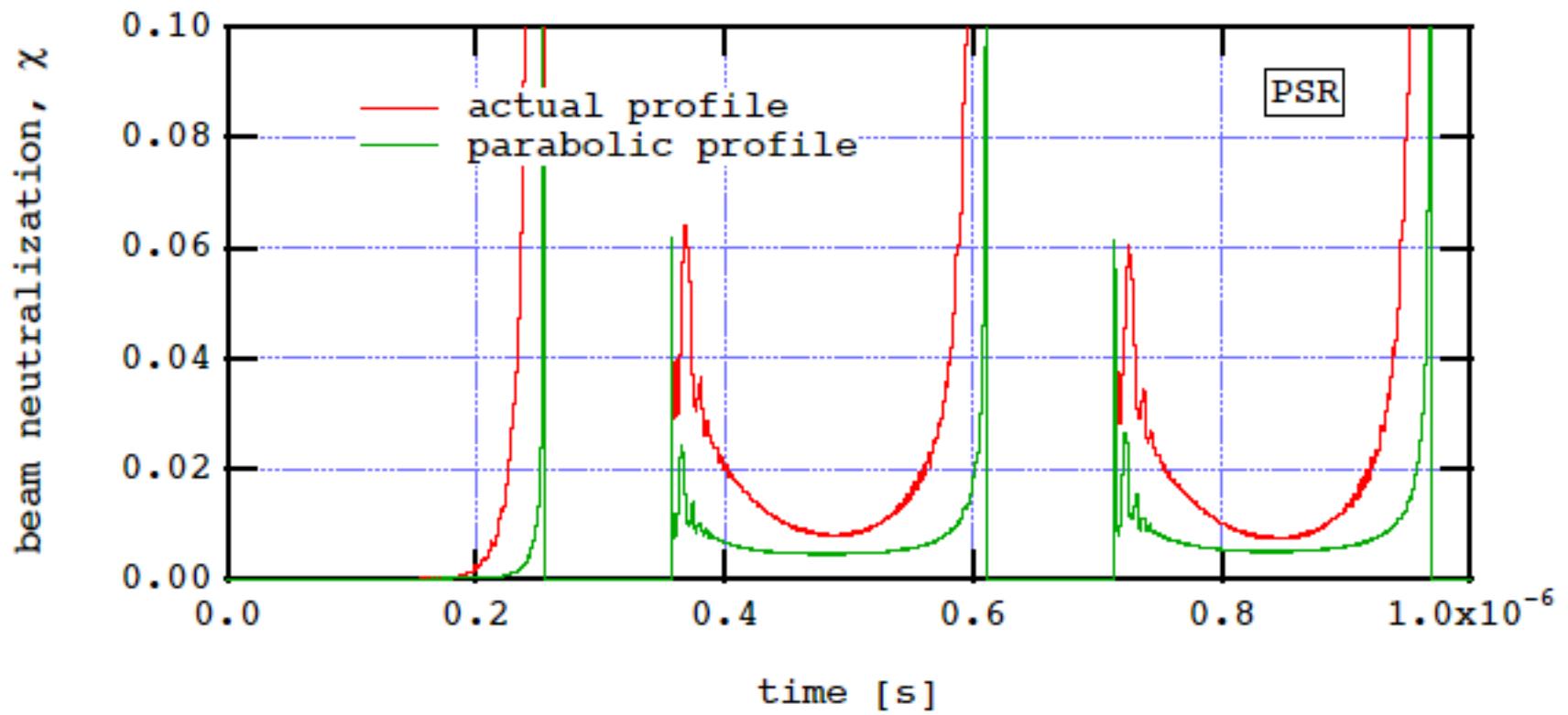


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Additional material



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31st ICFA Advanced Beam Dynamics Workshop on Electron-Cloud Effects "ECLOUDo4"

Napa (California), April 19-22, 2004



Sponsored by LBNL, CERN, ORNL and SNS



<http://www.cern.ch/icfa-ecloudo4>

This ICFA workshop will review experimental methods and results obtained within the past few years on the electron-cloud effect (ECE), along with progress on its understanding obtained from simulations and analytic theory, and the effectiveness of mitigation mechanisms. As in previous workshops dealing with the ECE (KEK, July 1997; Fermi, February 2000; KEK, September 2001; CERN, April 2002), the focus of ECLOUDo4 will be broad, covering all aspects of the phenomenon.

The workshop will take place in the Napa Embassy Suites (<http://www.embassysuites.com/1>), which will also be the official conference hotel. The deadline for abstract submission is January 10, 2004. The deadline for hotel reservations is March 21, 2004. Electronic proceedings will be published, and authors will be encouraged to submit their contributions to a special edition of FERMAT-AB (details on abstract submission, registration, hotel reservations and travel station will be mailed out and posted on the ECLOUDo4 website).

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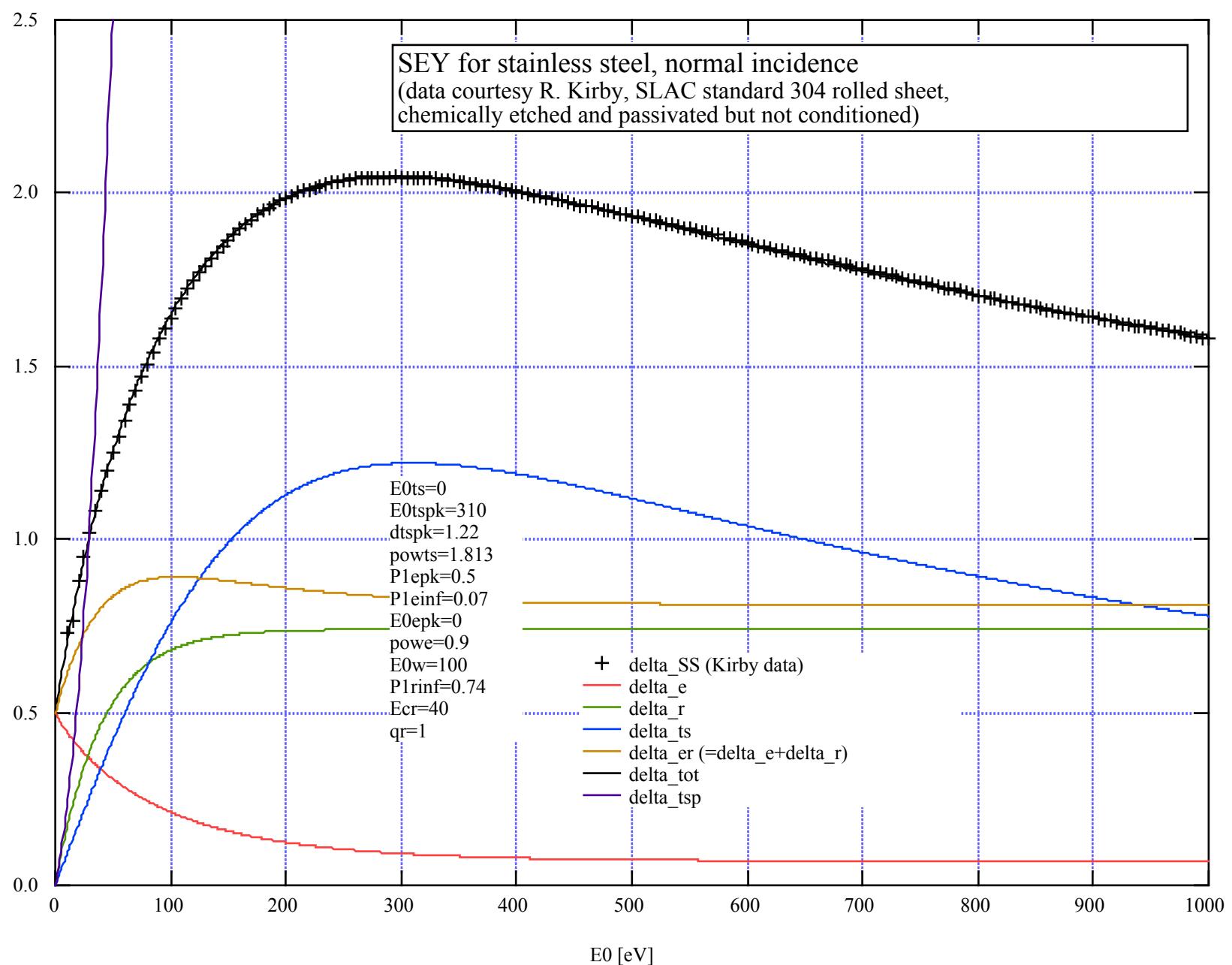
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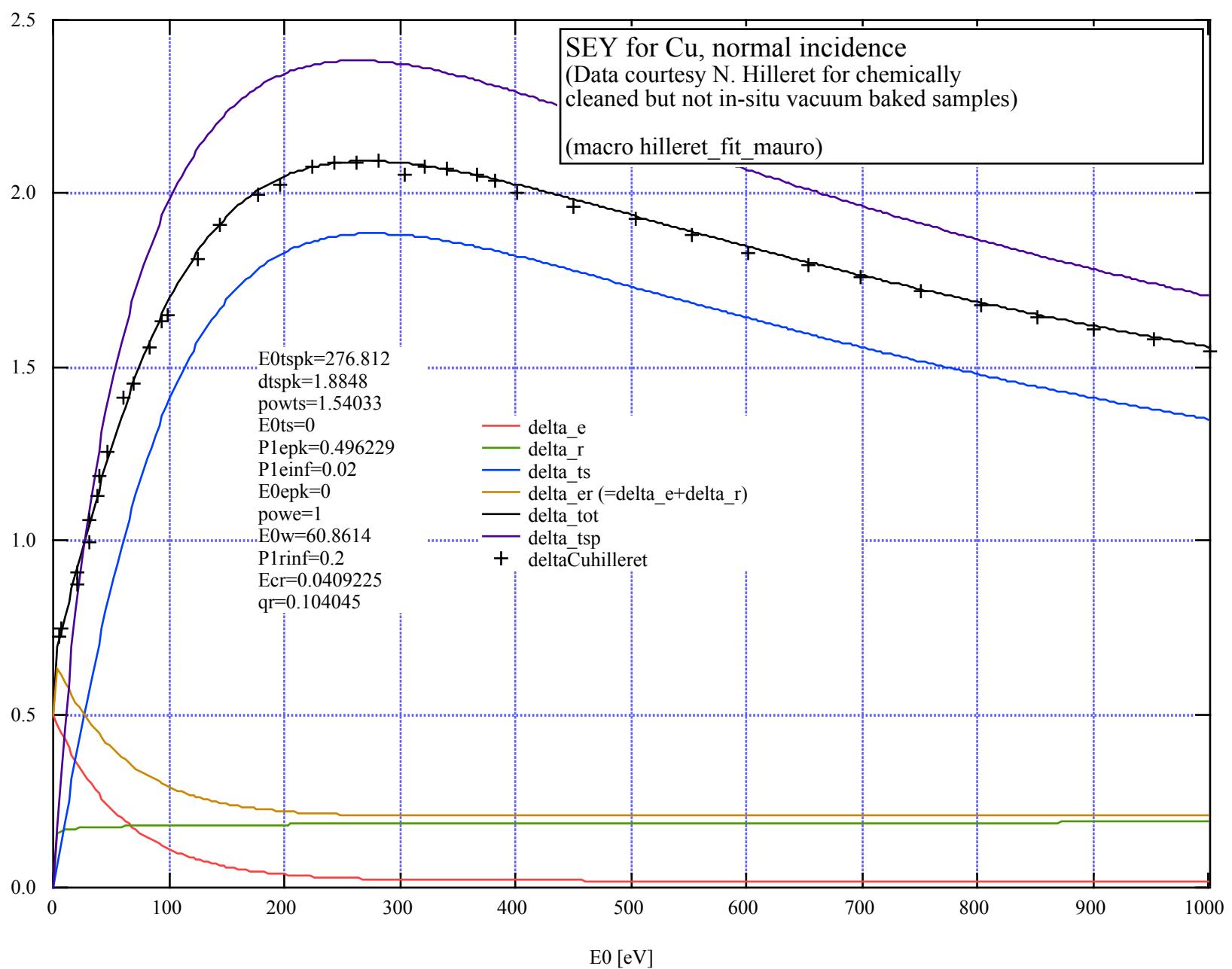
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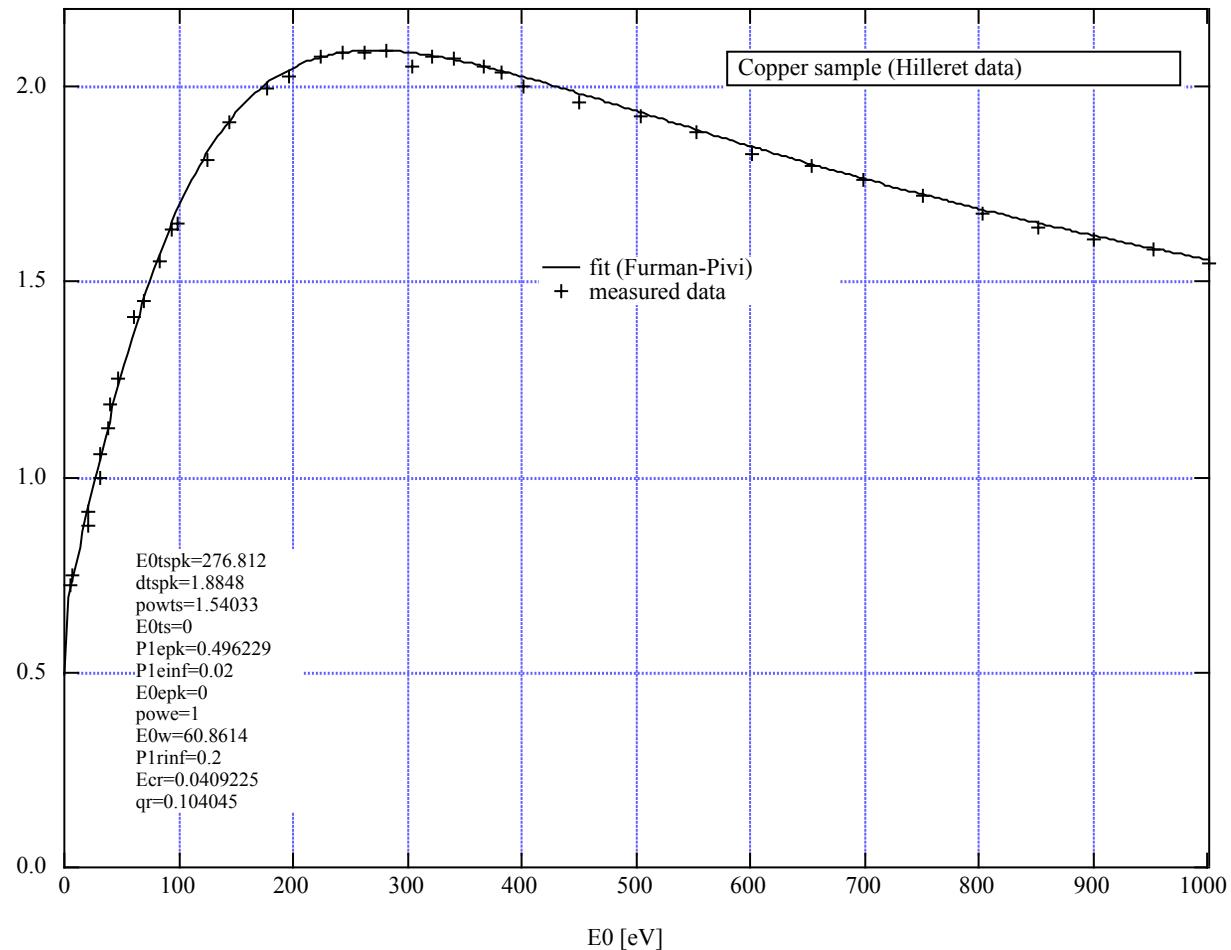


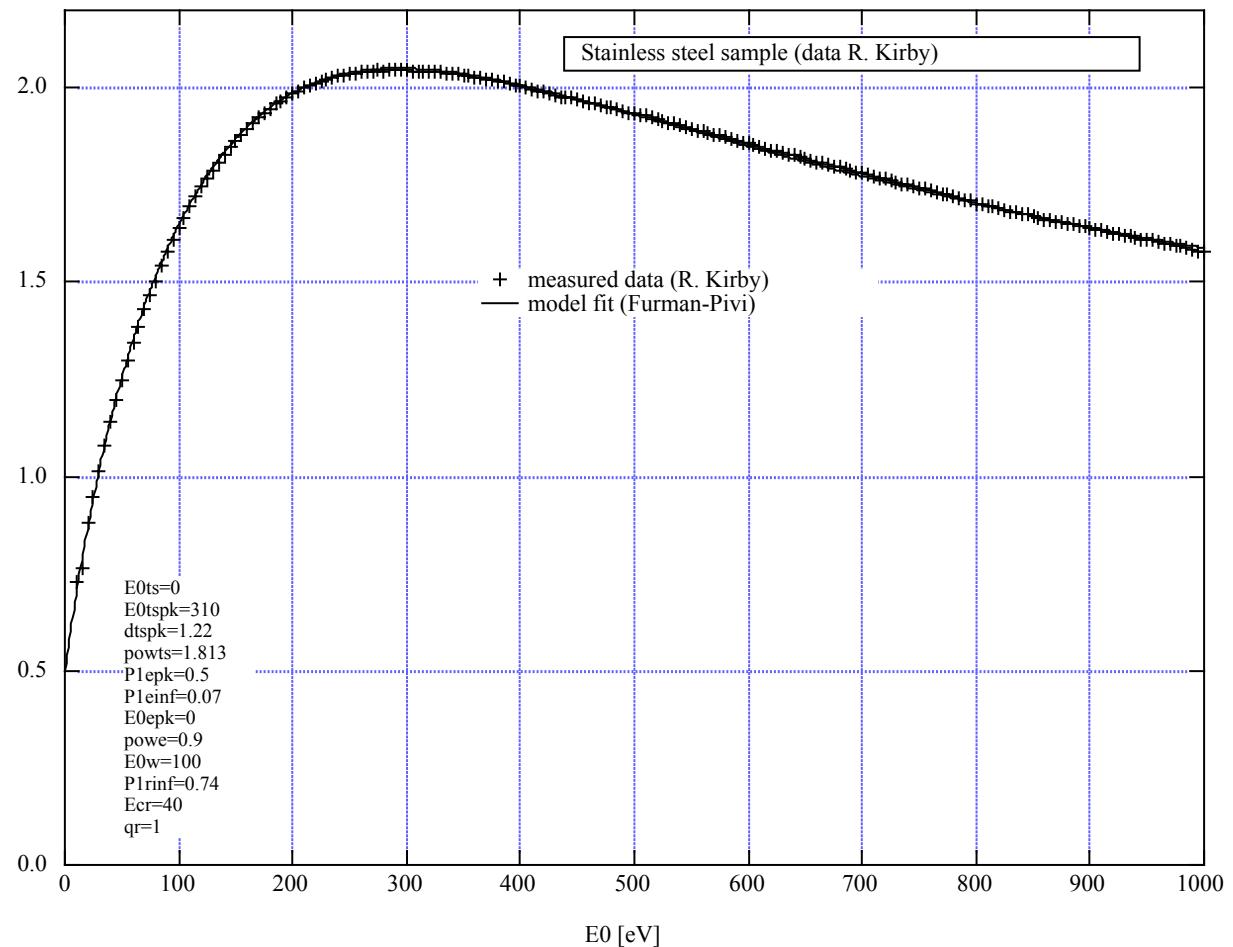


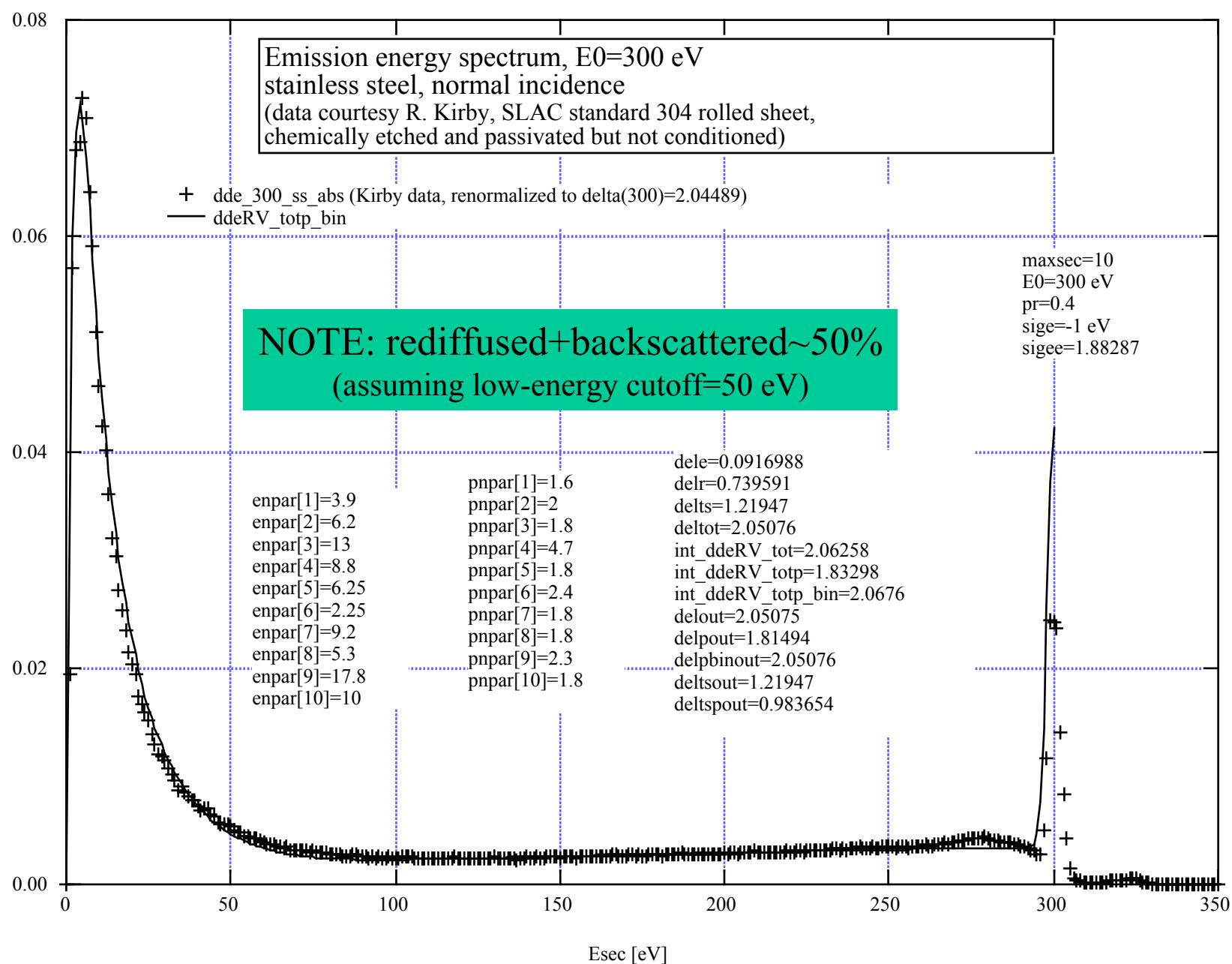
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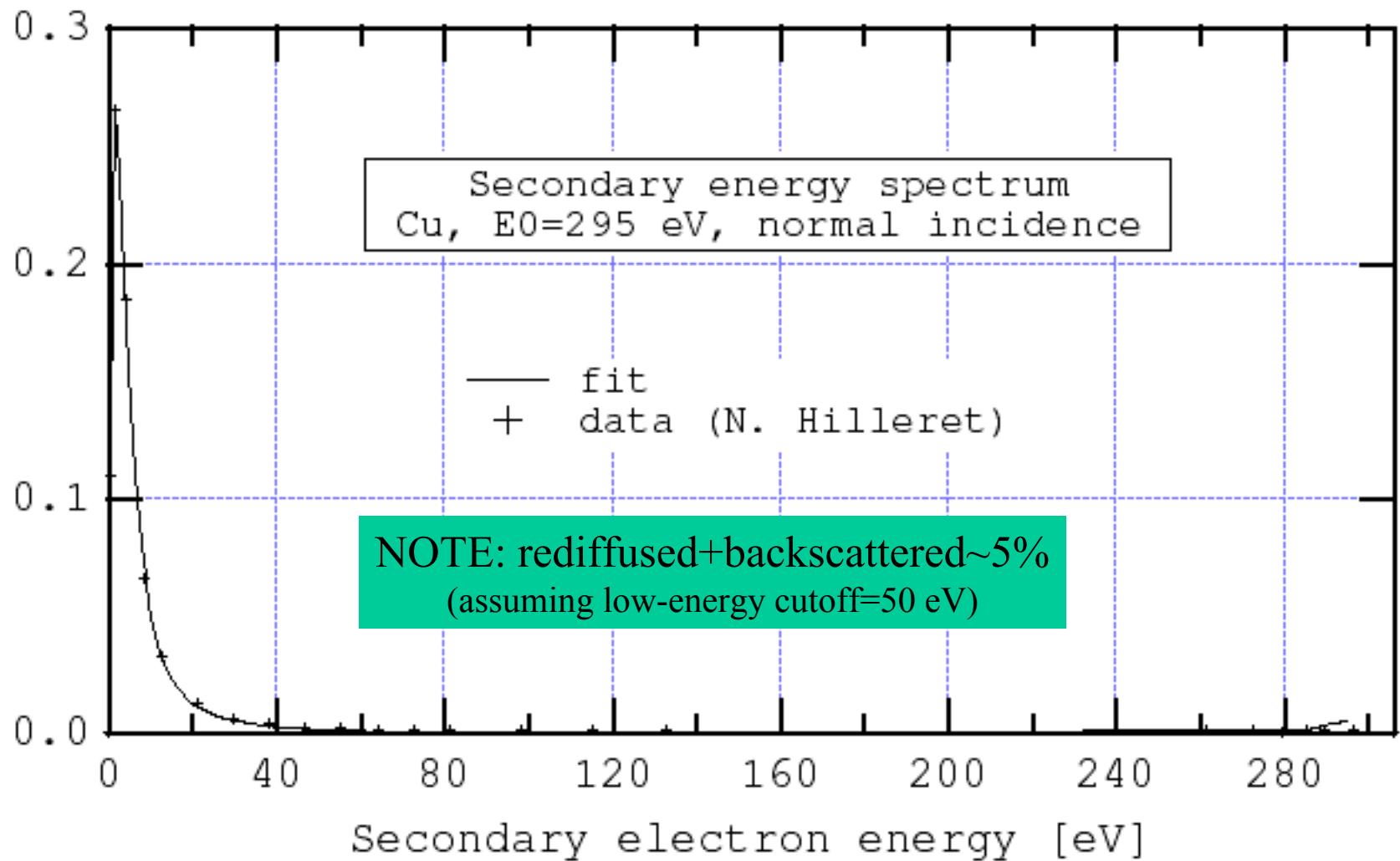
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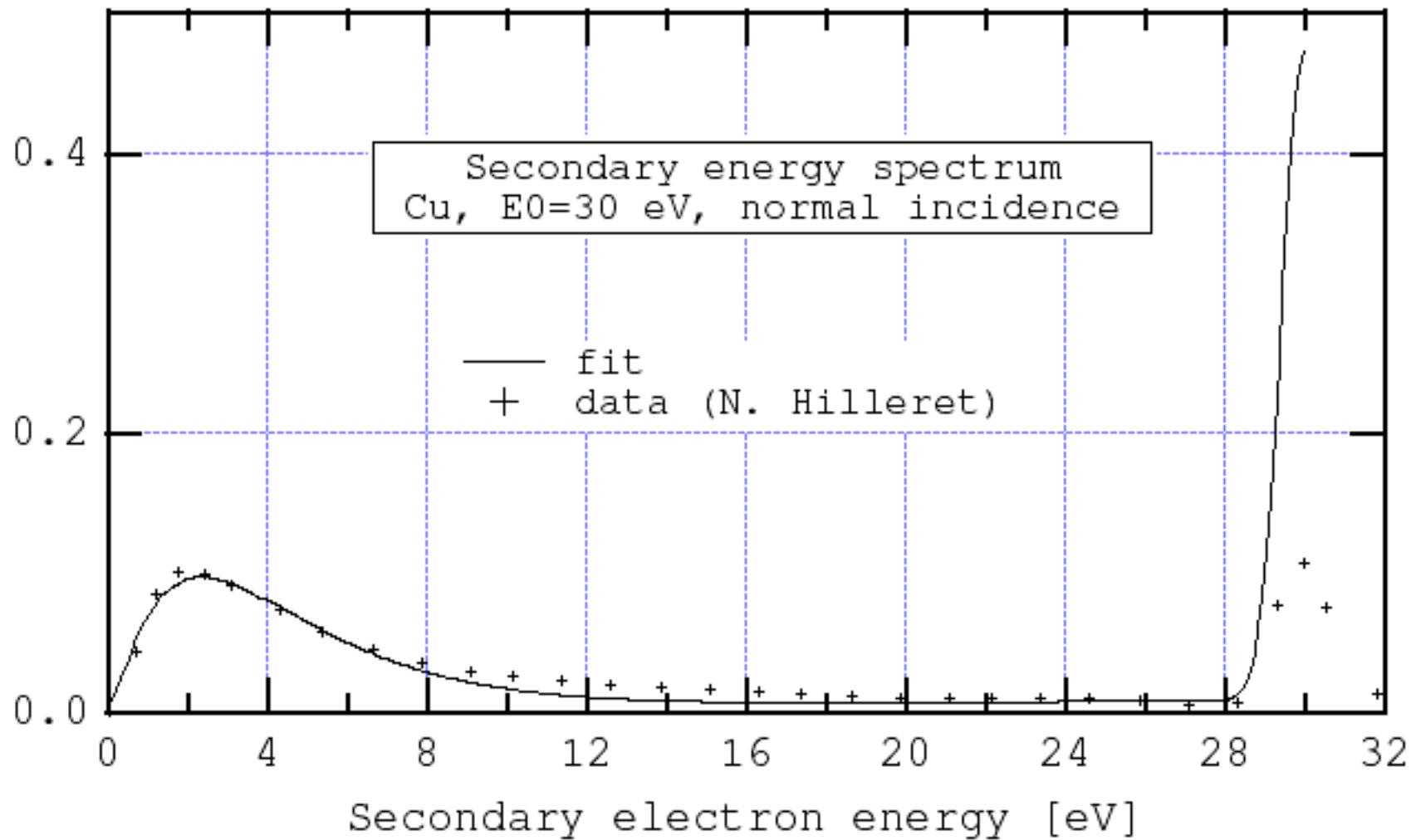


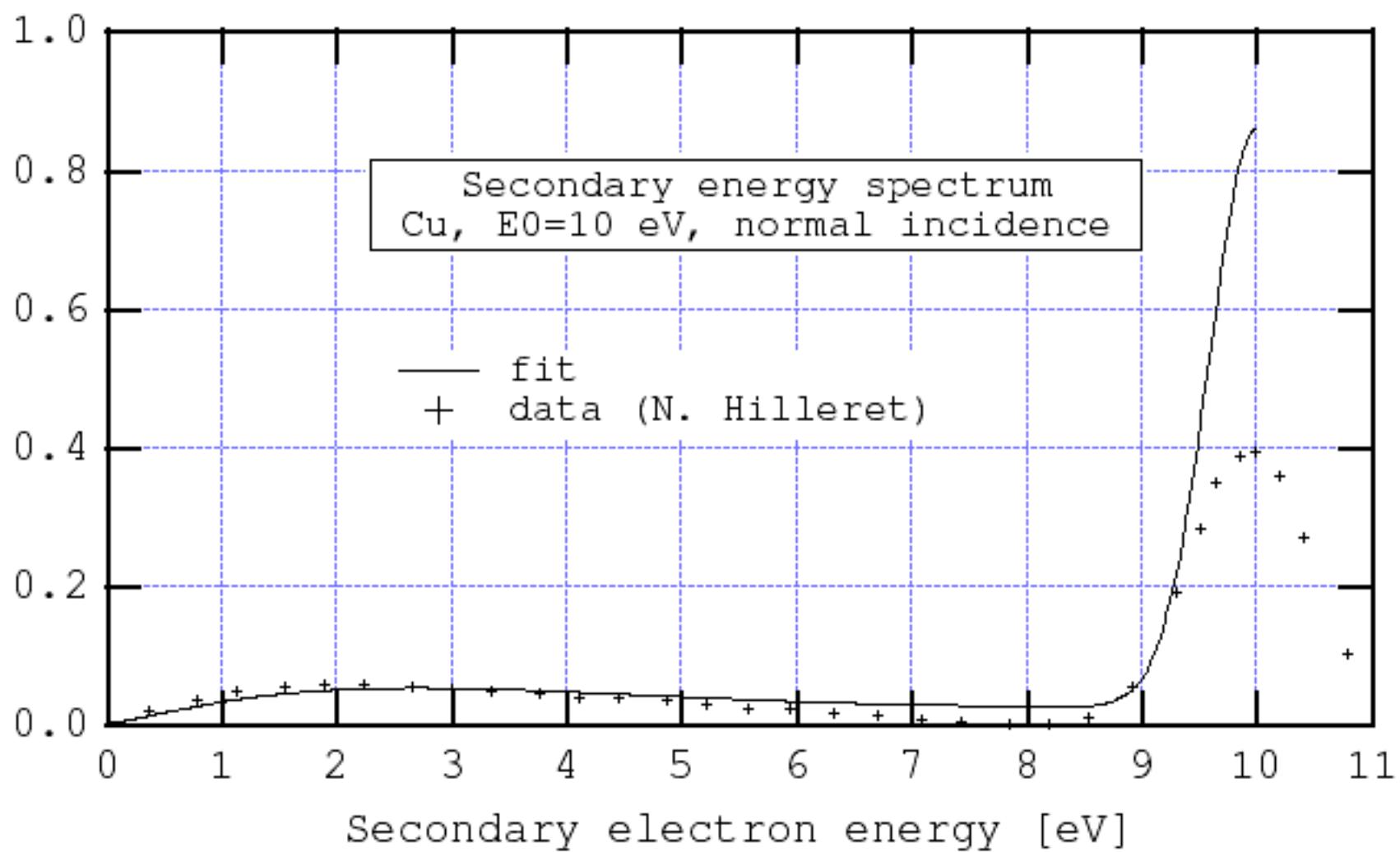




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Current parameter values from fits to data

Table 1: Model parameters.

	Cu	SS	POSINST name
Emission angular spectrum (Sec. 2.3.1)			
α	1	1	pangsec
Elastically backscattered electrons (Sec. 3.2)			
$P_{1,s}(\infty)$	0.02	0.07	Pisinf
$\hat{P}_{1,s}$	0.496	0.5	Piepk
\hat{E}_s [eV]	0	0	E0epk
W [eV]	60.86	100	E0w
p	1	0.9	pove
σ_e [eV]	2	1.9	sige
e_1	0.26	0.26	epar1
e_2	2	2	epar2
Rediffused electrons (Sec. 3.3)			
$P_{1,r}(\infty)$	0.2	0.74	Pirinf
E_r [eV]	0.041	40	Ecr
r	0.104	1	qr
q	0.5	0.4	pr
r_1	0.26	0.26	rpar1
r_2	2	2	rpar2
True secondary electrons (Sec. 3.4)			
$\hat{\delta}_{ts}$	1.8848	1.22	dtspk
\hat{E}_{ts} [eV]	276.8	310	E0tspk
s_0	1.54	1.813	powts
t_1	0.66	0.66	tpar1
t_2	0.8	0.8	tpar2
t_3	0.7	0.7	tpar3
t_4	1	1	tpar4
t_5	0	0	tpar5
t_6	0	0	tpar6
Total SEY[†]			
\hat{E}_t [eV]	271	292	
$\hat{\delta}_t$	2.1	2.05	dtotpk

[†] Note that $\hat{E}_t \approx \hat{E}_{ts}$ and $\hat{\delta}_t \approx \hat{\delta}_{ts} + P_{1,s}(\infty) + P_{1,r}(\infty)$ provided that $\hat{E}_{ts} \gg \hat{E}_s, E_r$.

Table 2: Further model parameters for the true secondary component.

	Cu	POSINST name
p_n	2.5, 3.3, 2.5, 2.5, 2.8, 1.3, 1.5, 1.5, 1.5, 1.5	pnpap(n)
c_n [eV]	1.5, 1.75, 1, 3.75, 8.5, 11.5, 2.5, 3, 2.5, 3	snpar(n)
SS		
p_n	1.6, 2, 1.8, 4.7, 1.8, 2.4, 1.8, 1.8, 2.3, 1.8	pnpap(n)
c_n [eV]	3.9, 6.2, 13, 8.8, 6.25, 2.25, 9.2, 5.3, 17.8, 10	snpar(n)



Q: is the electron emitted spectrum Maxwellian?

A: only approximately.

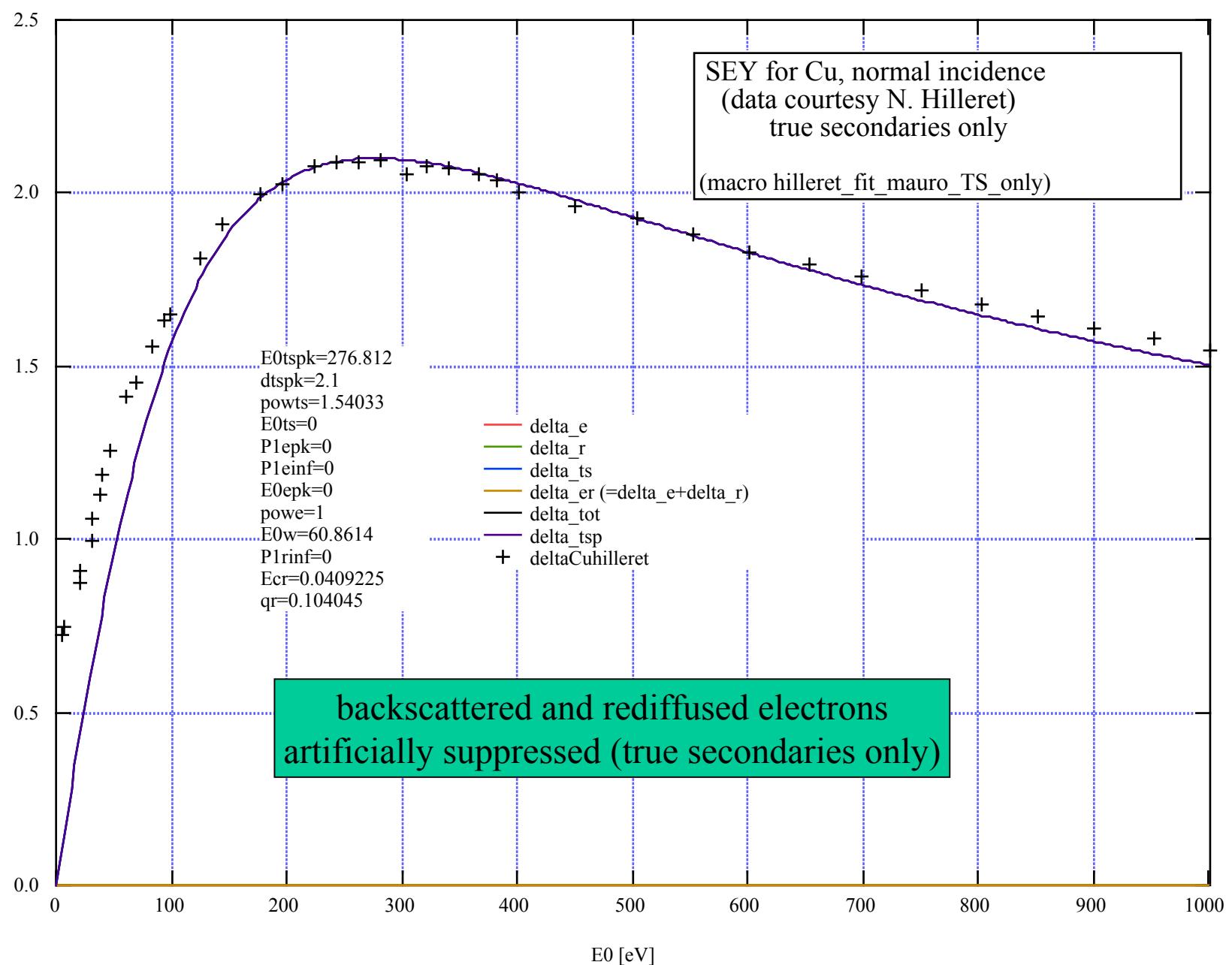
definition of Maxwellian spectrum:

$$\frac{dN}{d^3\mathbf{p}} \propto \exp(-E/kT), \quad E = \frac{\mathbf{p}^2}{2m_e}$$
$$\Rightarrow \frac{dN}{dE} \propto E^{1/2} \exp(-E/kT) \equiv E^{p_n - 1} \exp(-E/\varepsilon_n)$$
$$\Rightarrow p_n = 3/2$$

Fits to data, however, imply $p_n \sim 1.8-5$, depending on n and material



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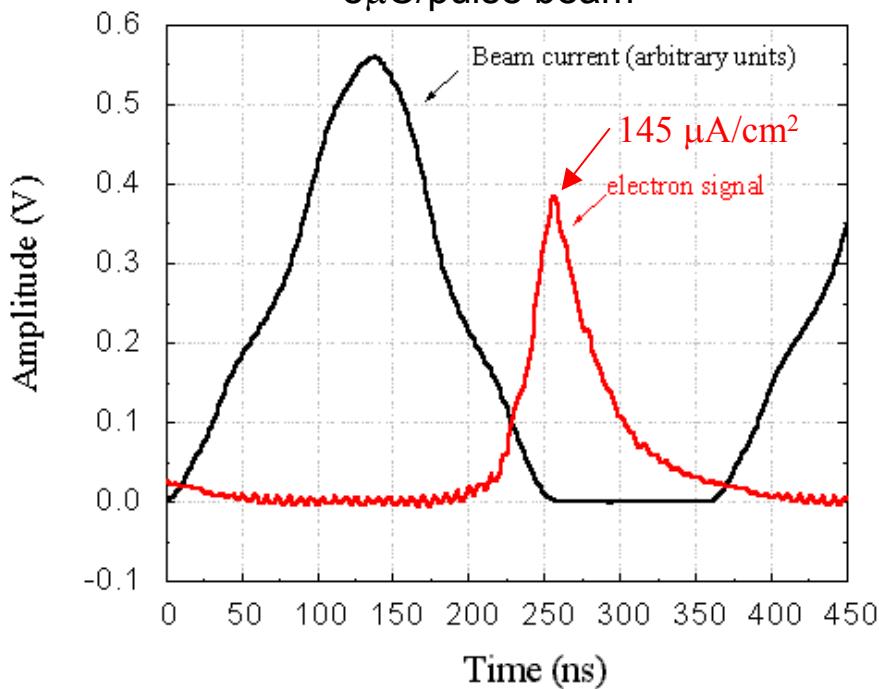


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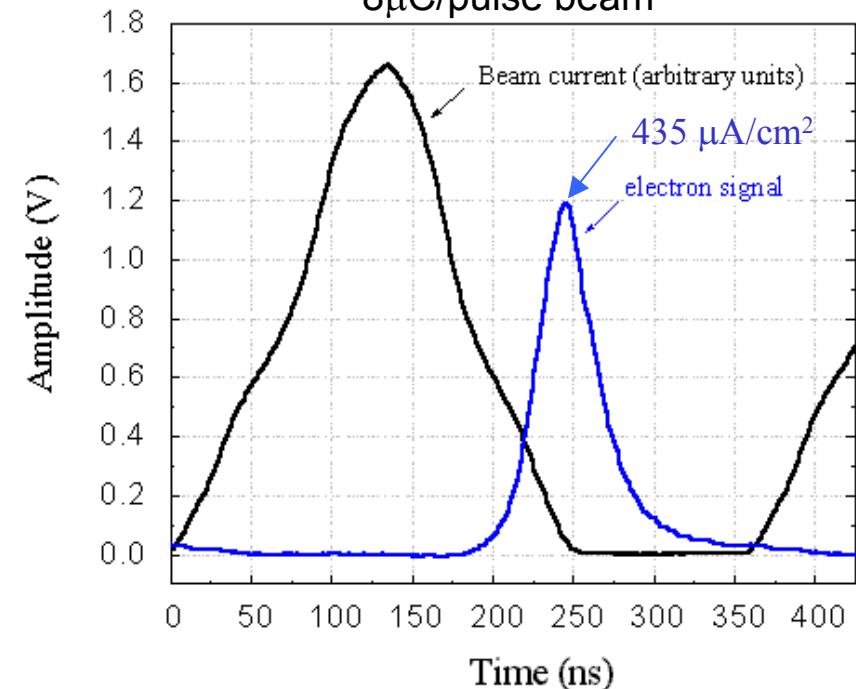
BIM for long bunches: case of PSR

- bunch length $\gg \Delta t$

ED02X electron detector signal
8 μ C/pulse beam

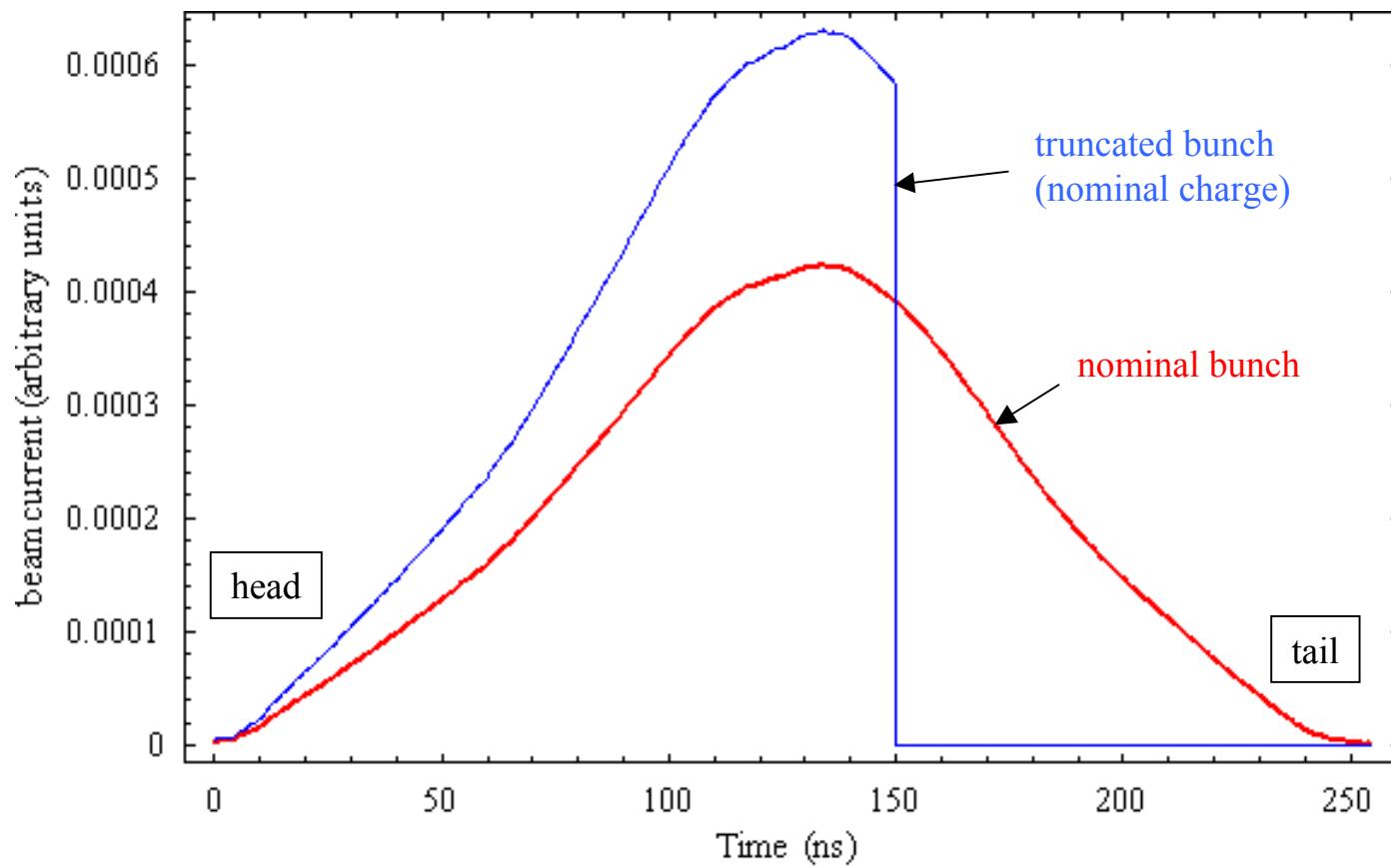


ED42Y electron detector signal
8 μ C/pulse beam

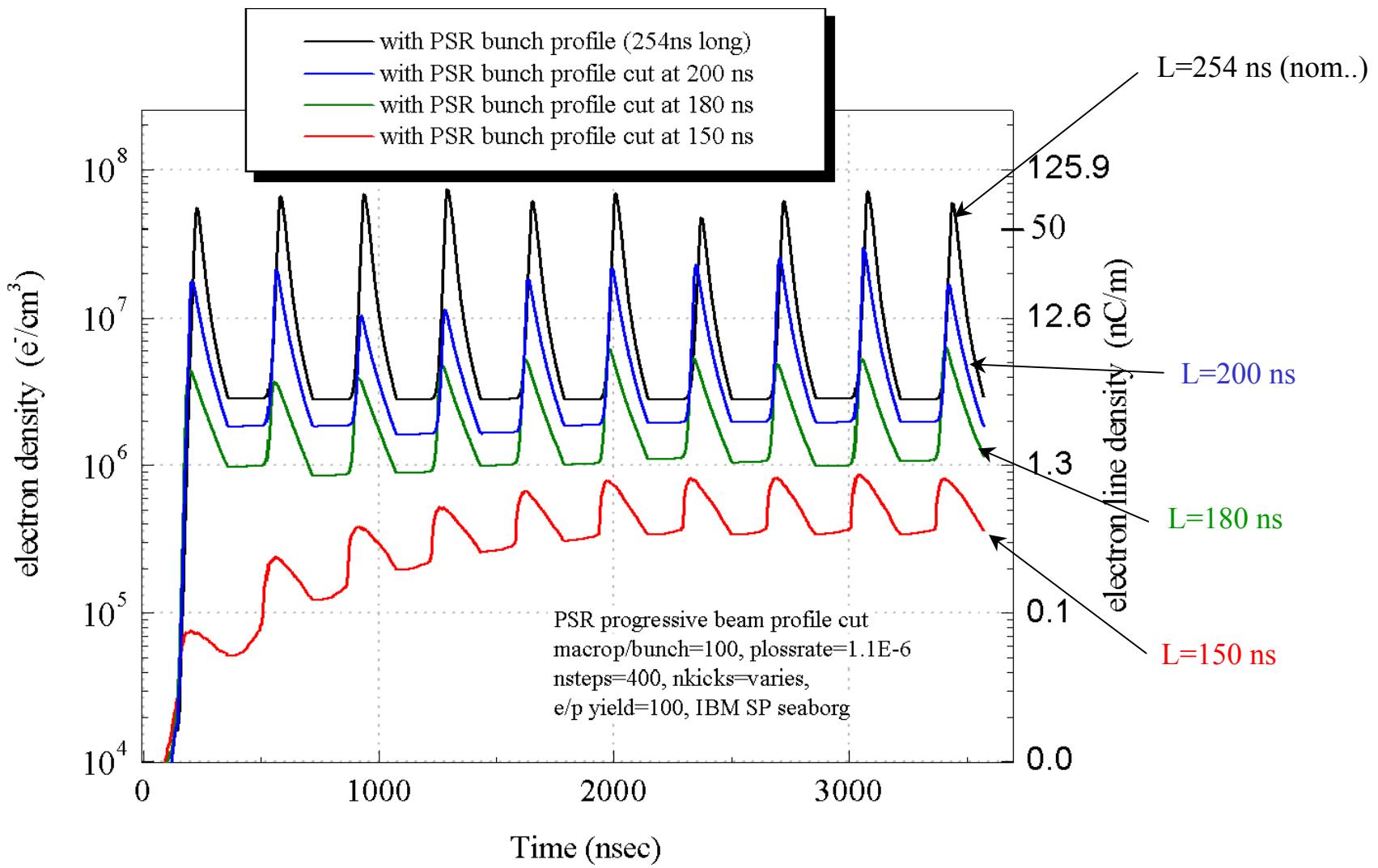


Effect of bunch shortening (PSR simulation; M. Pivi)

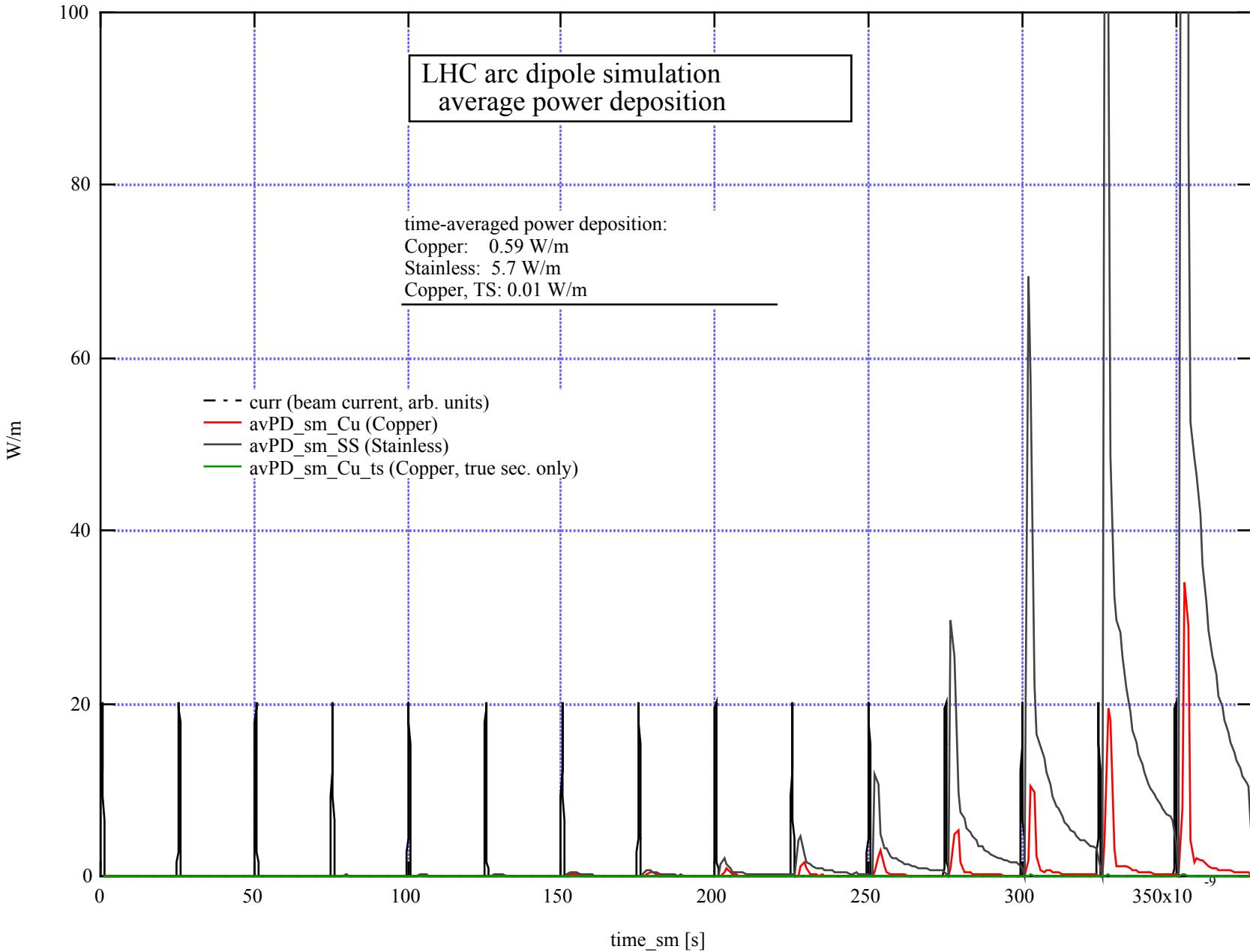
- truncate the bunch tail to reduce trailing-edge multipacting

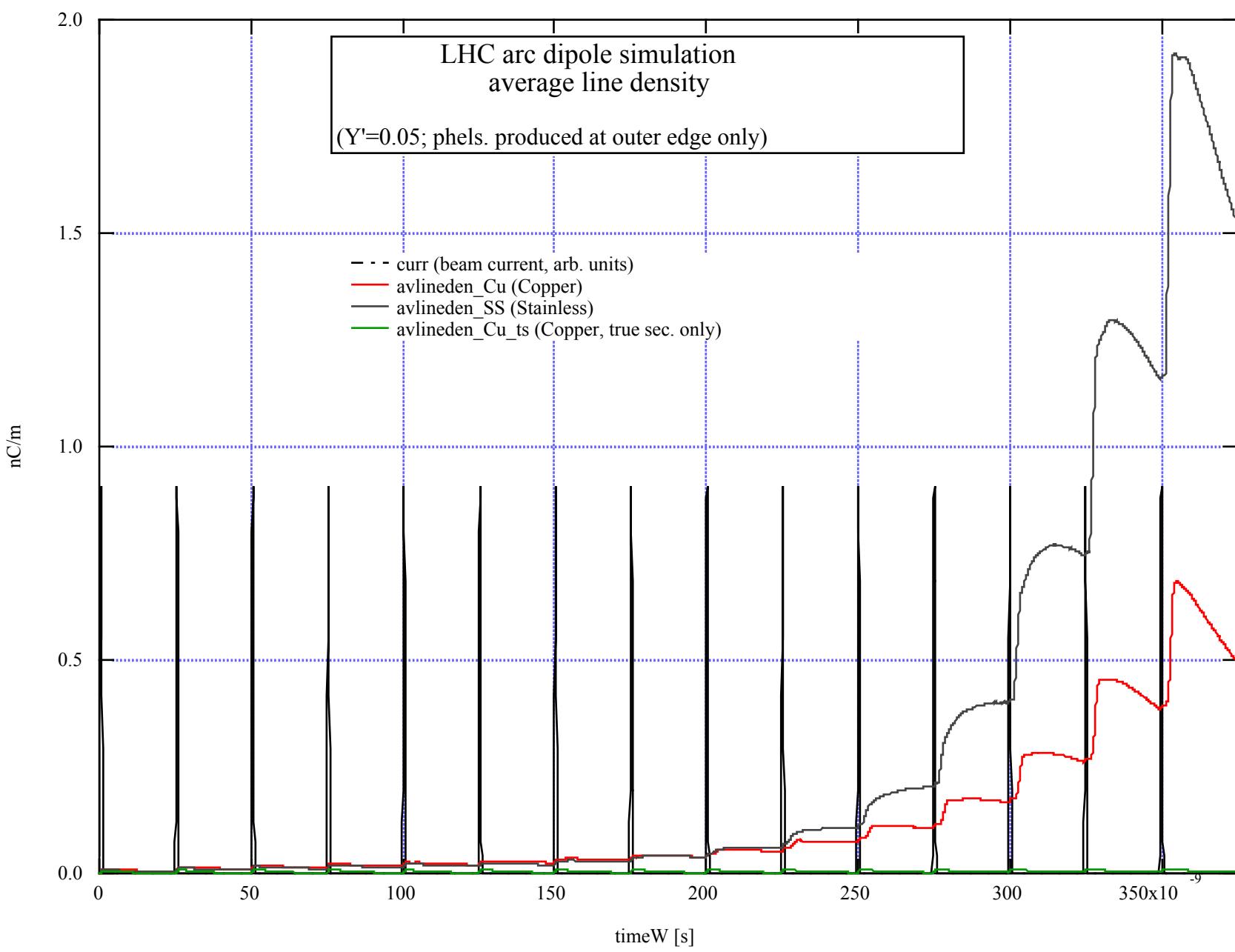


Effect of bunch shortening (PSR simulation; M. Pivi) – contd.

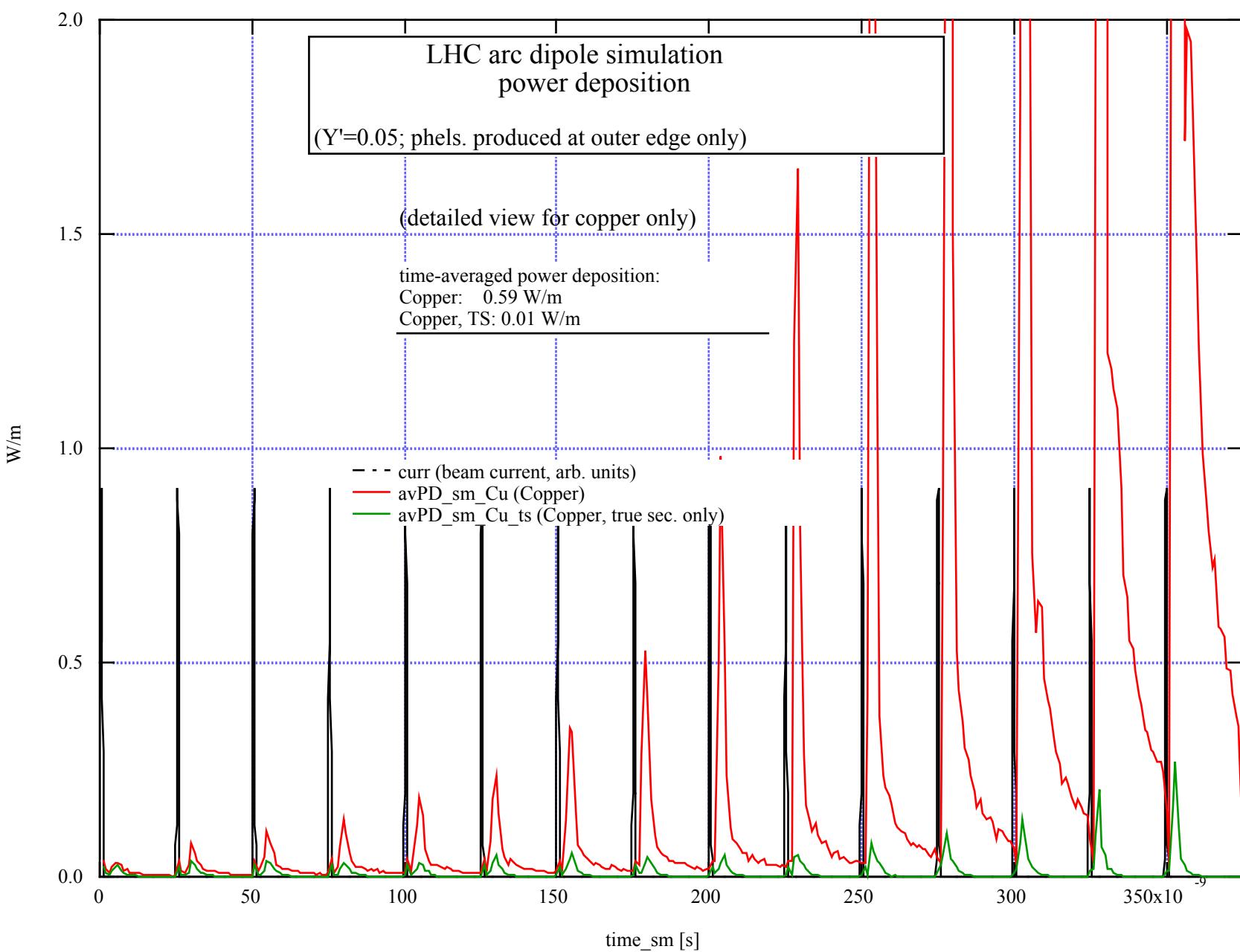


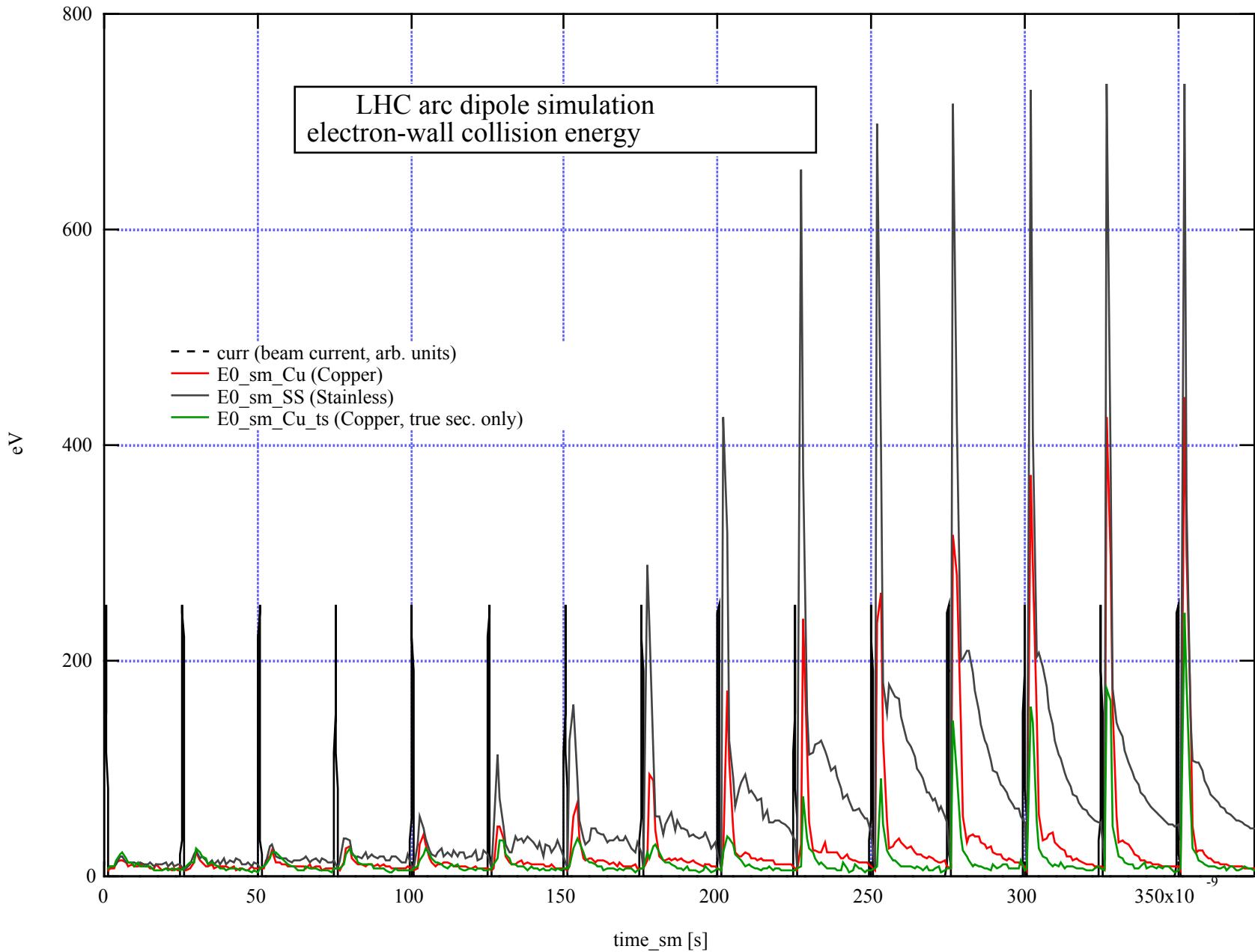
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